AD 260 012

11

ERRATA

The correct number of the second quarterly report on research and development of titanium rocket motor cases in accordance with Contract No. DA-19-020-ORD-5230 is

TECHNICAL REPORT NO. WAL 766.2/1-1

This notice should be filed with your copy of the report.

UNITED AIRCRAFT CORPORATION
Pratt & Whitney Aircraft Division

PRATT & WHITNEY AIRCRAFT

DIVISION OF UNITED AIRCRAFT CORPORATION

EAST HARTFORD 8, CONNECTICUT, U.S.A.

Rockets, Motor Cases
Titanium Fabrication
Titanium Alloys

Second Quarterly Report on Research and Development of Titanium Rocket Motor Case

61-4-1
NOX

By

R. P. Brody
Frank C. Crosby Jr.

January 31, 1961

Pratt & Whitney Aircraft Division
United Aircraft Corporation
East Hartford 8, Connecticut

Contract No. DA-19-020-ORD-5230
OCO R&D Branch Project No. TB4-004
Department of the Army Project No. 5B93-32-004

TECHNICAL REPORT NO. WAL 766.2/2

Qualified requestors may obtain copies of this report from the Armed Services Technical Information Agency, Arlington Hall Station, Arlington 12, Virginia.

TECHNICAL REPORT NO. WAL 766.2/2

[illegible]WORD.

This inte[illegible]t was prepared by the Pratt & Whitney [illegible] of United Aircraft Corporation, East Har[illegible], in complianc[illegible] Contract No. DA-[illegible]. It covers the t[illegible]ical accomplishment on th[illegible]evelopment of titanium rocket motor ca[illegible]onth period from October 1 through [illegible].

TABLE OF CONTENTS

LIST OF FIGURES

List of Figures (continued)

List of Figures (continued)

List of Figures (continued)

LIST OF TABLES

List of Tables (Continued)

I. INTRODUCTION

A. Purpose and Scope of Project

This program is aimed at the development of a high strength, lightweight, titanium alloy pressure vessel, of the type used for solid fuel rocket motor cases. B-120VCA titanium alloy has been selected for further investigation because of its inherent high strength, its potential of reliably exceeding the yield strength/density ratio of 1,000,000 inches and the possibility of reaching 1,200,000 inches. The main problems involved in its application include the development of fabrication techniques to achieve consistently high strength levels along with the most economical use of material.

B. Background Information

Previous research and feasibility testing conducted by Pratt & Whitney Aircraft Division have indicated that B-120VCA titanium alloy is an excellent material for lightweight rocket motor cases. Evidence was accumulated that its properties could be improved, as well as the techniques used in fabrication. This alloy contains thirteen per cent vanadium, eleven per cent chromium, and three per cent aluminum. In the cold-worked and aged condition it has achieved the highest strength/weight ratio of all metals that have been used for rocket motor cases. Work at Pratt & Whitney Aircraft Division has demonstrated that this alloy may be fabricated into small pressure vessels with yield strengths above 180,000 pounds per square inch. At this stress level the material has a strength equivalent to 290,000 psi in low alloy steel at the same strength/density ratio. B-120VCA titanium alloy has also displayed excellent corrosion resistance to salt spray environment at the 160,000-170,000 psi yield strength level, an important consideration where long time storage is involved.

C. Subject Matter Covered in This Report

The work planned on the various phases of the program is outlined and the results of all current investigations are reported. These results include the following:

1. Tensile tests, chemical analyses, and micro-examination of press-forged pancake DGT-2,

2. Techniques for hydrogenation of B-120VCA sheet stock,

3. Fracture toughness (G_c and modified Charpy impact) tests of forty-inch diameter flow-turned cylinders,

4. X-ray diffraction studies of cold-rolled sheet stock and flow-turned material,

5. Tensile, bend, and fracture toughness (G_c) tests of tungsten-inert-gas and electron-beam welded sheet stock, and

6. Limited tensile tests of pancake forgings upset at high and low strain rates.

The above results are discussed and tentative conclusions drawn.

II PROGRAM PLANNED

The following program is planned at the present time and is subject to revision as the development progresses. Major emphasis will be directed to the study of metallurgical factors which influence material behavior during forging, flow-turning, heat treatment, and welding. The results of this study will be applied to the achievement of reliability in full scale components at the 180,000 psi yield strength level with the most economical use of material. The feasibility of extending the reliable yield strength level to 200,000 psi will also be determined.

As a result of delays and the revised pace given to the program, it is now apparent that it cannot be completed in the time called for by the contract. This matter and the possibility of an extension will be discussed in meetings with the technical supervisor. The status of the material to be used in the program is outlined in Table I.

A. Effects of Interstitials

The effects of hydrogen content on delayed cracking and stress-corrosion are to be studied, with emphasis on the flow-turned material used for the cylindrical section of rocket cases. The present PWA specification calls for a maximum hydrogen content of 0.015 per cent. When a satisfactory hydrogenation technique has been developed a limited hydrogen program will be conducted first on sheet stock. The material will be reduced fifty per cent by multiple-pass cold-rolling, hydrogenated to a level of 200 ppm, and aged to a yield strength of 180,000 psi. The aging heat treatment at 800F should act also as a diffusion heat treatment to eliminate any gradient in hydrogen content caused by the hydrogenation process. Smooth and notched (K_t=8) tensile specimens will be tested at five temperatures between -35F and 400F. Smooth and notched specimens will be tested at the standard strain rate (0.005 in/in/min) and the remaining notched specimens will be tested under sustained load.

It is expected that this initial program will establish test techniques, give an insight into the effects of test temperature, and aid in fixing the sustained-load stress levels, as well as determining the effect of hydrogen on delayed cracking.

The effects of oxygen content on aging response, notch sensitivity and stress-corrosion will be evaluated using nine press-forged pancakes. The oxygen levels being investigated are 0.10, 0.15, and 0.20 per cent, the hydrogen and nitrogen contents being maintained at 0.015 and 0.02 per cent respectively. After Wyman-Gordon has determined the aging response of the three pancakes forged with different oxygen contents, smooth and notched tensile testing will be conducted at the 160,000 and 200,000 psi yield strength levels. Stress-corrosion testing with salt spray will also be conducted on this material at the same strength levels. Additional pancakes with varying oxygen contents will be press-forged in sets of three, depending upon the results obtained with the first three.

B. Forging Practice

The primary aims of the forging portion of the program are to improve the strength and uniformity of end closures and to achieve more economical use of material. It is expected that these objectives will be attained by contour-forging of bosses, by reduction in wall thickness, and by controlling finishing temperature so as to retain the maximum amount of cold work.

1. Press Forging

Four pancakes 0.5 x 15 inches have been forged in open dies by Wyman-Gordon at two forging temperatures and at high and low strain rates. Four additional pancakes may be upset as duplicates or at other combinations of temperature and strain rate, depending upon the results of evaluation of the first series. The results of this work will be applied to the development of closed-die forging of fourteen-inch diameter domes by the "dogbone" technique. Forty-inch diameter front closures will be forged by this technique

if subscale results indicate this to be the most promising forging method.

2. Hammer Forging

Two of the four pancakes 1 x 18 inches to be upset by Ladish will be hammer-forged in closed dies. The initial billet breakdown for the first two pieces will be performed at 1900 and 2000F, and final forging will be completed at 1700F. The other two pancakes will be forged as duplicates or at an intermediate temperature. The latter pancakes will contain an offset boss so that fourteen-inch diameter domes can be produced if desired. Forging will begin during February, 1961. Full scale front closures will be forged by this technique if mechanical property evaluation of the above subscale pancakes and domes is more promising than the press forging results.

3. Ring Rolling

Ladish will conduct ring rolling studies on six fourteen-inch diameter rings. An additional six rings will be fabricated for flow-turning development. The first four pieces will be forged as follows:

Piece	Billet Upset Temperature	Ring Rolling Temperature
1	1800F	1800F
2	1800	1900
3	1800	2000
4	1700	To be based on preceding results.

These four rings will be rolled during February and will be sectioned for evaluation of mechanical properties and microstructure. Two additional rings will be rolled as duplicates or at intermediate temperatures depending upon the above results.

The rolling technique which develops the best microstructure and mechanical properties after ring rolling and flow-turning will be applied to rolling the remaining six rings to be used for flow-turning development. Based on these results, seven forty-inch diameter rings will be rolled under optimum conditions. One of these will be sectioned for evaluation and the others flow-turned for evaluation and possible use in rocket cases. In addition, full scale rear closures will be fabricated by the ring-rolling technique if subscale results are satisfactory.

C. Flow-Turning Development

The twelve fourteen-inch diameter roll-forged rings fabricated by Ladish will be flow-turned. The first four or possibly six of these rings will be flow-turned using the best present technique. The remaining rings will be used to investigate major flow-turning parameters such as the mandrel rpm, rate of roller travel axially, and per cent reduction per pass. The cylinders resulting from this work will be explored for mechanical properties with emphasis on fracture toughness. The cylinders will be used to determine the effect of 200 ppm of hydrogen on delayed cracking. X-ray diffraction studies will be conducted to determine the effect of the various flow-turning parameters on degree of preferred orientation and hence on directionality of mechanical properties. Forty-inch diameter rings will be flow-turned after the small scale work has progressed sufficiently.

D. Weld Development

The weld development work is aimed primarily at improving the fracture toughness of welds in B-120VCA titanium alloy. Fracture toughness testing of TIG welds by Pratt & Whitney Aircraft Division and by the Naval Research Laboratory has shown low G_c values. The initial work will be on establishing the best fracture toughness test technique and on the evaluation of the electron-beam welding process. Techniques for weld repair will also be investigated.

E. Metallographic Studies

Light microscope examination of flow-turned material, forged end closures and TIG welds has shown variations in structure and grain boundary constituent which are believed to be associated with poor mechanical properties and with unsatisfactory behavior during fabrication. Representative samples of the above will be analyzed at Battelle Memorial Institute by electron microscopy and by microprobe techniques.

III TEST RESULTS

A. Mechanical Properties of Past Forgings

An extensive survey of the tensile properties, composition, and microstructure of Wyman-Gordon press-forged pancake DGT-2 has been conducted to determine the extent of and the reasons for variations in yield strength with respect to the original billet center. This pancake was forged from half of a billet which had been split longitudinally so that after forging the original billet center was located at the periphery of the pancake. Pancake DGT-2 was chosen for examination from a group of three because it had received a double upset, it represented the larger (fourteen-inch diameter) billet stock, and it had shown considerable variation in yield strength in the preliminary testing. It was considered that the double upset would be more representative of full scale end closures than the single upset, and that the larger billet diameter would be more likely to reveal any effect of non-uniformity in the ingot.

Duplicate slugs were cut from DGT-2 in twenty-seven locations across the pancake diameter. These locations represented the top, center, and bottom of the pancake, and radial positions extending from the original billet center through the pancake center to the original pancake surface. The slugs were aged at 900F for 96 hours, machined into round tensile specimens, and tested at room temperature. The tensile properties and specimen locations are shown in Table II. There was considerable variation in yield strength with a tendency for higher values towards the billet surface as compared to the billet center. The yield strength and radial location are plotted in Figure 1. A statistical analysis of variance has established that there is a significant trend in yield strength, increasing from the original billet center to the billet surface. There is no question that the exceptionally high yield strength adjacent to the billet surface is the greatest factor in producing this trend (Table II). Thickness measurements of the pancake have shown a definite difference in thickness at the original billet center from that at the billet surface, the billet surface location being the thinner by about 0.100 inch. This thinning could indicate a greater reduction and more work during forging, thereby locally increasing the aging response and yield strength.

There was also a significant variation in tensile ductility with location but this variation did not correspond to the differences in yield strength. Most of the specimens showing low elongations came from the pancake center and were associated with coarse grain size (Figure 1). Metal flow in this area is more restricted than in the periphery of the pancake and higher temperatures would be expected. Coarser grain size at the center of the pancake is indicative of less work, coupled with a higher finishing temperature. A few scattered areas of low elongation were evident away from the pancake center (Table II). These low elongations are generally attributable to forging practice and are not believed to be related to location in the original billet.

Frequency distribution plots of yield strength differences between duplicate specimens for pancake DGT-2 and cold-rolled and aged B-120VCA sheet stock are shown in Figure 2. These plots show that the differences between duplicate specimens from pancake DGT-2 are apparently within normal test scatter as judged by the sheet stock distribution. The average differences were very close: 3.17 ksi for the sheet stock and 3.19 ksi for pancake DGT-2.

It was felt that oxygen content would be the most probable composition factor influencing the observed differences in yield strength. Higher oxygen contents would be expected at the original billet surface. Oxygen is an alpha stabilizer and it is known to have a strong influence on the aging response of this alloy. The data measured on pancake DGT-2 at Wyman-Gordon shows that the observed trend in yield strength is evident after aging at 900F for 24, 48, and 72 hours, as well as after aging at 900F for 96 hours. Aging curves for various locations are shown in Figures 3, 4, and 5. The yield strength at various specimen locations is plotted in Figure 6. To establish a possible correlation between yield strength and oxygen content, samples from the tensile specimens at all twenty-seven locations on the pancake section were analyzed with the results shown in Table II. A statistical analysis has shown no correlation between these values of oxygen content and the yield strength variations. The specimens which had low tensile elongation were completely analyzed for composition with the results shown in Table III. There appeared to be no consistent relation between variation in any composition element and ductility.

It has been reported by the AD Hoc Committee on Chemical Analysis, Titanium Alloy Sheet Rolling Panel, Ordnance Materials Advisory Board, that the consistent determination of oxygen content in B-120VCA titanium alloy is exceptionally difficult. The data presented in the committee's report was accumulated from various facilities using different analysis techniques on standard material samples. Material samples of the type used have been procured from Watertown Arsenal Laboratories and are being analyzed to compare results with those of other facilities as to magnitude and variation of oxygen content. It is possible that a correlation between yield strength and oxygen content of pancake DGT-2 has been hidden by inconsistencies of the analytical method.

Microexamination of pancake DGT-2 in both the as-forged and the forged-and-aged conditions has shown considerable variation in grain size, amount of apparent working, and degree of recrystallization, as stated in the first quarterly report (PWA-1897). These structures had no apparent connection with original billet locations but appeared to be a result of the forging operation alone. The only significant fact evident in the as-forged microstructures was a greater amount of working at the billet surface and the pancake surface compared to other areas of the pancake (Figures 7 and 8). This area of greater working corresponded to the higher strength region at the original billet surface (Table II). Microexamination in the forged-and-aged condition showed that higher strength is associated with a finer distribution of aging constituent (Figures 9 and 10). Examination of specimens having low tensile elongation indicated that low ductility resulted from a semicontinuous network of aging constituent at the boundaries of recrystallized grains (Figure 11). Specimens with higher (more than 4.0 per cent) elongations showed transgranular failure across unrecrystallized grains (Figure 12).

Duplicate slugs from nine locations corresponding to original billet center, pancake center, and billet surface of pancake DGT-2 were heat treated at 1450F for one hour, aged at 900F for 96 hours, machined into smooth tensile specimens and tested at room temperature. The 1450F heat treatment was intended to simulate the drawing operation on full scale end closures. The tensile properties and specimen locations are shown in Table IV. These results indicated more uniformity and slightly higher yield strengths than the forged-and-aged properties (Figure 13). The tensile elongations, however, are much lower

than those for forged-and-aged material (Table II, Figure 13). Microexamination showed that these properties can be attributed to the recrystallization which occurred during the 1450F heat treatment. This recrystallization produced a more uniform structure (Figure 14) and therefore a more uniform strength, but it also caused complete networks of aging constituent at grain boundaries and uniformly low ductility. Tensile fracture surfaces indicated that failure was almost completely intergranular (Figure 15). The material properties after the 1450F heat treatment and aging indicate that severe overaging has occurred after 96 hours at 900F. Six additional slugs from pancake DGT-2 heat treated at 1450F for thirty minutes are being aged for 24, 48, and 72 hours to further investigate the overaging effect.

Information has been received from the Ladish Company on the comparison of material from three metal suppliers. The compositions and tensile properties are shown in Tables V and VI. These data were accumulated by Ladish in acceptance testing of the material. The results show differences in aging response of material from the three sources, and corresponding variations in ductility. The yield strength and elongation of these various heats of material are plotted in Figure 16. No difference in relative ductility is shown by these data. There were no significant differences in composition except that material from metal supplier C appeared to have a lower average chromium content (Table V). This difference had no apparent effect on tensile properties (Table VI). Similar comparative data are being obtained from Wyman-Gordon.

B. Effects of Interstitials

All work so far on the effect of hydrogen has been on the establishment of a hydrogenation technique. First, hydrogenation in aqueous solutions of hydrofluoric and nitric acids was attempted. This technique was unsatisfactory because it produced a high hydrogen content at the surface and produced an intergranular surface attack. The second method tried was to expose the material to a hydrogen atmosphere at 400 to 600F. This technique was abandoned because the desired 200 to 300 ppm of hydrogen could not be obtained with reasonable hydrogen pressures and exposure times. Information received from metal supplier A indicated that hydrogenation could be accomplished satisfactorily by a cathodic process. The process used

sulphuric acid as an electrolyte, a lead anode, and the titanium alloy sheet to be hydrogenated as a cathode. In preliminary trials, hydrogen levels up to 2460 ppm have been achieved, after a diffusion treatment at 800F. The parameters of the process are now being established for hydrogen levels of 200 to 300 ppm.

Half-sections of three press-forged pancakes with varying oxygen contents have been received from Wyman-Gordon. These pancakes were to have oxygen contents of approximately 0.10, 0.15, and 0.20 per cent. The oxygen analyses of the ingots were as follows:

			Oxygen Content	
Heat	Pancake	Desired	Top	Bottom
V-1676	DYO-1	0.10%	0.126-0.128%	0.227-0.202%
V-1677	DYN-1	0.15	0.158	0.183
V-1678	DYM-1	0.20	0.212	0.202

Heats V-1677 and V-1678 were close to the desired analyses but Heat V-1676 had a wide variation in oxygen analysis. These pancakes were forged with a double upset as outlined in Table VII. Wyman-Gordon is presently rechecking the composition and determining the aging response of the forgings at 900F.

Macroexamination at Pratt & Whitney Aircraft Division has shown coarse-grained regions at the pancake centers similar to the previous pancakes DCM-1, DGT-1 and DGT-2 (Figures 17, 18, and 19). The compositions on two surfaces and at the center of each pancake are being determined.

C. Fracture Toughness Testing

Fracture toughness (G_c) testing on forty-inch diameter flow-turned cylinders Nos. 1 and 2 from the Pershing program has been completed. The material was machined into the ASTM standard 3 x 12 inch internally-notched specimens shown in Figure 20 (except that these specimens did not include welds). Specimens were tested in both the axial and circumferential directions. Both cylinders were tested as-stress-relieved (850F for 30 minutes), and cylinder No. 2 after aging at 800F for one, two and four hours. The G_c results and corresponding tensile properties are shown in Table VIII and Figure 21. Smaller ASTM standard specimens 1 x 4 inches and 2 x 8 inches are being machined from cylinder No. 2

to determine the effect of specimen size. The results to date indicate that the toughness (G_c) is lower in the circumferential direction than in the axial. This is understandable since the yield strength is higher in the circumferential direction. The toughness is approximately equivalent at a given yield strength level regardless of direction (Table VIII, Figure 21).

Modified Charpy impact specimens (Figure 22) and instrumented bend test specimens have been machined in the axial and circumferential directions from flow-turned cylinder No. 2. An attempt will be made to correlate the results on these specimens with the G_c test results. If a satisfactory correlation is found to exist, it may be possible to eliminate the expensive G_c test method, or to use it only as a final test method after screening tests with specimens of the above type. Test results on modified Charpy impact specimens at room temperature and -35F shown in Table IX indicate considerable variation. The room temperature data exhibited a slight trend towards higher energy absorption in the circumferential direction as compared to the axial. The -35F data were too limited to show an effect of direction but indicated a slight trend towards lower energy absorption than the room temperature results. Energy absorption and yield strength are plotted in Figure 23. Modified Charpy impact testing so far has shown that the sensitivity of the test technique at room temperature and below is not adequate. Additional impact specimens will be tested at 70, 215, and 400F, and instrumented bend specimens w be tested at room temperature.

D. X-Ray Diffraction Studies

The preliminary x-ray diffraction studies of mill-annealed and cold-rolled sheet and of flow-turned material have been completed and the results reported by Manufacturing Laboratories, Cambridge, Massachusetts. A copy of this report is included in Appendix C. The samples analyzed had been machined from mill-annealed sheet 0.125 inch thick, cold-rolled sheet stock (fifty per cent reduction) aged at 850F for thirty minutes, and the 40-inch diameter Pershing flow-turned cylinder No. 2 (fifty per cent reduction) also aged at 850F for thirty minutes. The results of this study were as follows:

1. Cold-rolled sheet and flow-turned material exhibit a distinct texture whereas mill-annealed sheet is randomly oriented.

2. The texture of flow-turned material varies across the wall thickness, and differs from that of cold-rolled sheet.

3. The principal working direction in flow-turning is circumferential,

4. The outer section of flow-turned material has a singular texture, similar to one component of what would be expected from rolling in the circumferential direction, and

5. The inner section of flow-turned material is of a mixed character, consisting of the outer section texture and a texture expected for rolling in the axial direction.

These results predict that the transverse mechanical properties of cold-rolled sheet should be similar to the axial properties of a flow-turned cylinder. Similarly the longitudinal properties of cold-rolled sheet should resemble the circumferential properties of the inner section of a flow-turned cylinder. The fact that the outer section of flow-turned material has a singular texture indicates considerable directionality in its mechanical properties. Since the inner section has a mixed instead of a singular preferred orientation it should exhibit little or no directionality. These predictions are verified by the observed results shown in Table X.

E. Weld Development

Preliminary testing on the initial set of TIC and electron-beam welded panels has been completed. Three panels of mill-annealed sheet 0.125 inch thick were TIG welded with B-120 VCA filler wire. Helium was used for the torch, trailer cup, and quenching gas. The panels were welded with solid copper backup and hold down bars using a travel speed of five inches per minute, an arc voltage of about ten, a current of about 125 amperes, and a tungsten electrode 0.093 inch in diameter.

Panels were electron-beam welded by Hamilton Standard at a travel speed of twenty-eight inches per minute, a voltage of 115 to 135 kilovolts, and a current of 3.0 to 4.4 milliamperes. Three panels were welded from mill-annealed sheet 0.125 inch thick. Two additional panels were welded from cold-rolled sheet reduced thirty-five per cent to a thickness of 0.085 inch and aged at 800F for four hours prior to welding. The intent of the aging treatment was to produce a yield strength level of about 180,000 psi.

Tensile, bend, and fracture toughness (G_c) tests on specimens from these panels have been completed. Modified Charpy impact specimens notched at the weld center and instrumented bend specimens have been machined from the TIG welded panels and are ready to be tested. Tensile and bend test results for both the TIG and electron-beam welded panels are shown in Table XI. Greater bend ductility is indicated for the electron-beam welded material. The tensile properties show lower elongation for the electron-beam welded specimens and higher yield strengths for those welded in the cold-rolled and aged condition. These differences are not representative of the strength and ductility of electron-beam welds. The low tensile elongation measured over gage lengths of one-half and one inch is a result of a very localized deformation in the narrow (0.050 - 0.073 inch) weld bead characteristic of the electron-beam weld. This localized deformation is believed to be caused by a slightly concave weld face and by the ductile nature of the weld material as compared to the parent metal. The localized yielding also gives artificially high yield strengths because the deforming material is strengthened by the adjacent high strength parent material as demonstrated by the test results from panels Nos. 357 and 358 (Table XI).

Fracture toughness (G_c) specimens were machined from TIG welded panels with notches at the weld centers per Figure 20. One specimen from an electron-beam welded panel was machined in accordance with Figure 20 and the remainder per Figure 24. The fracture toughness test results are shown in Table XII together with previous data from NRL on P&WA TIG welded panels. The toughness of TIG welds tested under this program was comparable to that obtained by NRL on similarly welded material, with one exception. The exception (1480 in-lbs/in^2) is considered significant because the specimen was

machined from an area which had only slight but complete weld penetration. This slight penetration was accompanied by finer grain size and less evidence of grain boundary constituent, indicative of a faster cooling rate as shown by comparison of Figures 25 and 26. Typical macrostructure of TIG welds is shown in Figure 27. The grain size in this area was 0.012 inch as compared to 0.015 inch in TIG welds with normal penetration.

The fracture toughness results on electron-beam welded material are more difficult to interpret because of the influence of specimen size. The single 3 x 12 inch specimen had a G_c of 795 in-lbs/in^2 which is higher than the average value for TIG welded material. The 1 x 4 inch specimens also gave higher values than TIG welded material but this result may not be significant because of the difference in specimen size. The notched tensile strengths of these small specimens are encouraging because they are close to the ultimate tensile strength of the material (Tables XI and XII). The latter specimens had a stress concentration factor of K_t=18.

Based on bead testing and a limited amount of fracture toughness (G_c) testing, it appears that the ductility of electron-beam welds is superior to that of TIG welds. This probably can be attributed to the faster cooling rate in electron-beam welding which results in less grain boundary precipitate and finer grain size. The average grain sizes in electron-beam welds were 0.095 inch in material 0.085 inch thick and 0.011 inch in material 0.125 inch thick as measured on transverse sections.

To further evaluate the electron-beam welding process a proposed program is being prepared. It will be submitted to Hamilton Standard, Airco, and National Research Corporation for quotations on performing the work. This program would involve 1) the determination of the effects of electron-beam welding parameters on microstructure, and 2) the determination of the mechanical properties of the most desirable structures.

To determine the effect of crack orientation in TIG welding the testing of a specimen containing two longitudinal welds with a transversely oriented notch in each weld (Figure 28) is being considered. A series of panels are being TIG welded to evaluate this specimen and the biaxial-stress weld specimen used by Curtiss-Wright (Figure 29). In addition, edge-notched specimens (K_t = 8) and further impact specimens will be tested. Various methods for increasing the cooling rate of the TIG weld puddle are being considered.

F. Forging Practice

1. Press Forging

Half-sections of four press-forged pancakes have been received from Wyman-Gordon. Two pancakes were forged in a single upset at 1700F and two at 1850F. One of each pair was forged at a high strain rate and the other at a low strain rate. The forging procedures followed are outlined in Table XIII. Wyman-Gordon is presently determining the aging response of these pancakes. The data received so far is shown in Table XIV. The tensile properties indicate a faster aging response for the pancakes upset at low strain rates, and lower yield strengths towards the pancake centers than at the pancake surfaces (Table XIV). Macroexamination showed coarse-grained regions at the pancake centers. There was also a tendency towards coarser grain size after forging at a high strain rate (Figures 30, 31, 32, and 33). There was no appreciable difference in the grain size of pancakes forged at 1700F and those forged at 1850F. The coarser grain size and slower aging response after forging at high strain rate is believed to be due to the higher finishing temperature as compared to that for the low strain rate forging (Table XIII).

2. Hammer Forging and Ring Rolling

The Ladish Company has completed acceptance testing of the heat of material that will be used in the first part of the hammer forging and ring rolling program. The composition was as follows:

Ingot Location	V	Cr	Al	Fe	C	H_2	O_2
top	13.60%	11.67	3.72	0.27	0.0172	0.0017	0.15
bottom	13.69	11.74	3.41	0.28	0.0183	0.0030	0.11

The tensile properties at 70F determined by Ladish are shown in Table XV. The results showed a trend towards higher strength at the ingot top than at the bottom. To minimize this effect and to avoid the effects of possible variations in composition, the material for hammer forging will be taken from one end of the ingot and the material for ring rolling from the other end. If sufficient material is available, samples for hammer or roll forging will be taken at intermediate locations as a check on composition variations along the ingot.

IV DISCUSSION

A. Exploration of pancake DGT-2, which was forged under joint study by Wyman-Gordon and Pratt & Whitney Aircraft Division prior to the current contract, has demonstrated that open-die forging can develop a wide range of tensile properties within a given part. Low ductility in the center of the pancake was found to be associated with a greater degree of grain boundary recrystallization than elsewhere in the forging (Figures 11 and 12). Insufficient localized working coupled with higher local temperatures are suggested as explanations for this behavior. The relatively high finishing temperature (1565F) and the long aging time of 96 hours at 900F to develop a yield strength of 180,000 psi are indications of the unusual behavior of this forging. Forgings of this type normally develop the desired tensile properties after 9 to 40 hours at 900F. Also of interest is the fact that fine aging precipitate in pancake DGT-2 was associated with higher yield strength (Figures 9 and 10). Samples with lower yield strength had coarser aging precipitate.

B. The differences in texture between inner and outer surfaces of flow-turned material shown by x-ray diffraction are in agreement with the mechanical properties for the respective locations (Appendix C, Fig. 7). The variations in crystallographic orientation shed some light on the nature of the deformation produced by flow-turning. In simplified form it appears that 1) the metal in contact with the roller tool is deformed spirally to a depth of at least 0.015 inch, and 2) the metal adjacent to the mandrel is moved axially as in cold rolling.

The x-ray diffraction work performed so far constituted an exploratory effort to ascertain whether it would be possible to detect any evidence of preferred orientation. Consideration is being given to determining the profile of the texture from the outside surface to the inside surface of flow-turned material. The nature of the residual stress, compressive or tensile, across the flow-turned section needs definition, and this may be capable of solution by x-ray diffraction techniques.

The significance of the preferred orientation encountered in the flow-turned section from a B-120VCA rocket case is not yet clearly understood. It is known that improved toughness is imparted by present flow-turning techniques. It may be possible to further improve toughness by varying the flow-turning parameters. Since it has been demonstrated that preferred orientation from x-ray diffraction analysis correlates with directionality of mechanical properties, the x-ray diffraction measurements would be useful in guiding the flow-turning development program to obtain optimum directionality of properties.

C. The work on press forging at low vs. high strain rates is incomplete but the data presently available indicate that for open-die press forging, low strain rates appear preferable to high strain rates at 1700 or 1850F forging temperatures. It also appears that the best result is produced by a finishing temperature of 1400F or below. An attempt will be made to define the relative importance of strain rate vs finishing temperature by forging one pancake from 1600F at a high strain rate and a second pancake from 2000F at a low strain rate, finishing both forgings below 1400F if possible.

These preliminary studies of strain rate and forging temperature were intended to uncover any extremes in forging practice which would produce unsatisfactory metallurgical behavior. The results will be applicable to closed-die press work and should provide suitable ranges of forging rate and temperature. The rate of heat extraction by the closed dies and the metal flow will undoubtedly govern starting temperature. Finishing temperature, however, will apparently dictate the eventual starting practice.

D. The relatively high G_c value of 795 in-lbs/in^2 obtained on an electron-beam welded sample points out the weld toughness which may be realized with this technique. Based on the limited data available, the ductility of electron-beam welds appeared to be superior to that of TIG welds. The exception to this trend was the unusual value of 1480 in-lbs/in^2 found in a section of a TIG weld. That the latter was a valid test was confirmed by the appearance of the fracture and the desirability of the fine grain size in welds was apparent. Although this condition was associated with marginal weld penetration, a condition considered impractical for circumferential case welds, this does not preclude the possibility of obtaining finer grained welds by changes in weld technique.

APPENDIX A

Tables

TABLE 1

Status of Material for OMRO Program

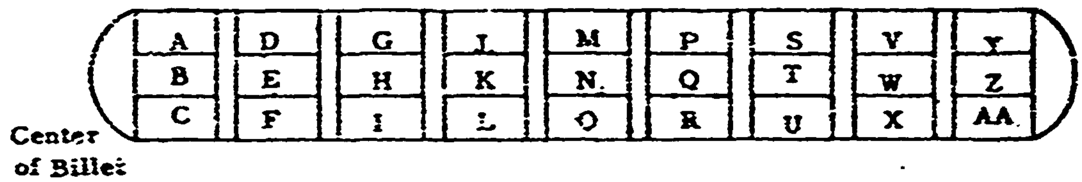
Test Program	Work Location	Material Composition	Type of Specimen	Status: Material	Status: Fabrication Instructions
Effect of interstitials (hydrogen)	PWA	PWA 1230	Sheet Stock	Received by PWA.	•
Effect of interstitials (oxygen)	Wyman-Gordon	Modified PWA 1200	Pancakes (9 pieces)	Received by Wyman-Gordon (9 pieces). Material for 1 piece reordered by Wyman-Gordon.	Three pieces forged and being evaluated. Forge 1 piece with 0.11% oxygen. Hold remaining material.
Weld improvement	PWA	PWA 1230	Sheet Stock	Received by PWA.	•
Press-forging	Wyman-Gordon	PWA 1200	High and low strain rate pancakes (8 pieces)	Received by Wyman-Gordon (8 pieces)	Four pieces forged and being evaluated. Forge two pieces at 16[illegible]F and 2000F. Hold remaining material.
Press-forging	Wyman-Gordon	PWA 1200	Contour-forged domes (14" diameter) ("dog-bone" technique) (8 pieces)	Received by Wyman-Gordon (4 pieces). Purchase order in process for remaining material.	Forge two pieces (first at 1750F). Hold remaining material.
Press-forging	Wyman-Gordon	PWA 1200	Full-scale front dome (40" diameter)	Do not order now.	•
Hammer-forging	Ladish	PWA 1200	Pancakes (4 pieces)	Received by Ladish (4 pieces)	Forge two pieces. Hold remaining material.
Hammer-forging	Ladish	PWA 1200	Full-scale front domes	Do not order	•

TABLE I
(Continued)

Test Program	Work Location	Material Composition	Type of Specimen	Status: Material	Status: Fabrication Instructions
Ring rolling	Ladish	PWA 1200	Rings (14" diameter) (12 pieces)	Received by Ladish (4 pieces). Purchase order in process for remaining material.	Roll four pieces.
Ring rolling	Ladish	PWA 1200	Rings (40" diameter)	Do not order.	-
Ring rolling	Ladish	PWA 1200	Full-scale rear domes (40" diameter)	Do not order.	-

TABLE II

Tensile Properties (70F) and Oxygen Contents of Pancake Forging DGT-2 after Aging at 900F



Tensile Properties

Specimen	Aging	UTS	Y. S. (0. 2%)	Y.S. (0.02%)	Elong.	R. A.	Oxygen Content
A	900F(96)AC	191.5 ksi	175.5 ksi	167.5 ksi	2.4%	7.5%	0.081%
A-1*	"	198.0	177.0	167.8	8.0	12.4	0.090
B	"	185.6	170.5	163.8	5.2	14.5	0.062
B-1	"	195.6	182.4	167.2	4.0	12.8	0.066
C	"	186.0	172.0	163.0	4.0	10.5	0.079
C-1	"	196.5	180.0	165.5	6.8	5.4	---
D	"	191.2	175.0	163.8	8.0	13.2	0.085
D-1	"	197.0	175.8	164.0	8.0	8.[illegible]	---
E	"	191.5	178.6	160.2	4.0	8.4	---
E-1	"	194.6	181.6	171.8	2.6	11.4	0.091
F	"	195.5	179.5	169.0	6.8	11.0	0.096
F-1	"	194.0	177.2	168.5	4.0	11.2	---
G	"	195.8	178.5	167.5	4.0	9.6	0.090
G-1	"	193.0	178.5	166.0	4.0	12.4	---
H	"	184.5	170.0	156.0	4.0	9.4	0.140
H-1	"	192.0	180.0	160.2	4.0	5.4	0.094
I	"	198.5	181.5	171.0	6.0	9.3	0.092
I-1	"	196.0	179.8	169.5	6.0	8.0	---
J	"	193.5	178.0	167.2	4.0	11.2	0.090
J-1	"	195.8	181.0	167.2	4.0	8.2	---
K	"	195.6	180.8	170.8	5.2	7.6	0.108
K-1	"	189.5	174.8	163.6	5.2	11.2	---
L	"	196.5	179.5	169.0	4.0	8.8	0.105
L-1	"	197.0	180.2	170.0	1.4	4.2	0.095
M	"	192.6	179.0	167.2	4.0	6.5	0.080
M-1	"	197.0	183.0	171.2	2.8	9.4	0.097
N	"	189.4	173.2	163.6	5.2	6.5	0.097
N-1	"	188.5	174.6	167.8	5.2	12.2	---
O	"	196.2	180.8	170.0	2.4	11.0	0.067
O-1	"	190.2	178.0	167.5	2.8	5.2	0.091

TABLE II
(Continued)

Specimen	Aging	UTS	Y.S. (0.2%)	Y.S. (0.2%)	Elong.	R.A.	Oxygen Content
P	900F(96)AC	191.0 ksi	177.5 ksi	166.5 ksi	6.0%	8.6%	0.151%
P-1	"	195.8	181.5	167.8	6.0	6.2	-
Q	"	203.0	188.0	175.4	4.0	8.8	0.117
Q-1	"	196.6	182.6	168.9	4.0	11.2	-
R	"	194.5	178.2	170.2	6.0	9.2	0.080
R-1	"	190.8	178.0	168.5	6.0	10.5	-
S	"	196.5	179.0	169.0	6.0	7.8	0.094
S-1	"	193.5	176.0	166.0	6.0	9.2	-
T	"	189.6	176.2	166.5	6.5	11.0	0.147
T-1	"	193.4	178.6	167.4	4.0	7.2	-
U	"	193.0	175.8	168.5	6.8	9.2	0.139
U-1	"	196.0	179.5	170.8	2.8	8.4	0.088
V	"	195.8	175.5	169.5	6.8	16.2	0.081
V-1	"	195.0	176.2	169.0	4.0	9.2	-
W	"	193.0	178.8	166.4	4.0	7.2	0.109
W-1	"	188.0	176.5	162.0	5.2	9.8	-
X	"	200.5	187.2	169.8	4.0	11	0.116
X-1	"	200.6	188.5	176.5	8.0	10.2	-
Y	"	200.0	183.2	163.2	5.2	6.5	0.102
Y-1	"	200.1	184.0	172.0	6.8	11.5	-
Z	"	195.0	176.2	160.0	4.0	9.4	0.097
Z-1	"	198.5	183.2	169.5	4.0	8.4	-
AA	"	207.3	192.0	179.5	4.0	10.5	0.112
AA-1	"	201.0	191.8	179.5	6.8	7.4	0.108

* Dash 1 specimens located behind those shown in the sketch.

TABLE III

Composition of Tensile Specimens from Pancake Forging DGT-2

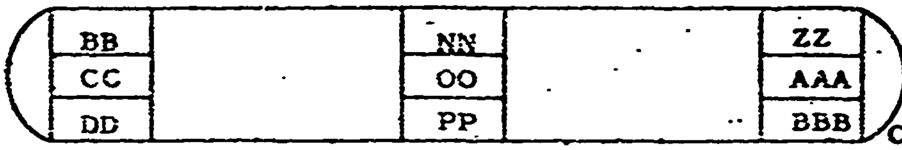
Specimen	V	Cr	Al	Fe	C	O_2	H_2	N_2
A*	13.00%	11.90%	2.70%	0.25%	-	0.081%	-	0.020%
A-1	13.20	10.90	2.68	0.17	-	0.090	0.006%	0.021
B	13.15	10.90	2.71	<0.5	0.08%	0.062	-	-
B-1	12.40	10.20	2.50	<0.5	0.06	0.066	-	-
E-1*	13.10	10.40	2.90	0.26	-	0.091	-	0.018
H	12.80	10.60	2.46	<0.5	0.06	0.140	-	-
H-1	13.40	11.10	2.30	<0.5	0.05	0.094	-	-
L	13.20	10.20	2.80	0.16	-	0.105	-	0.024
L-1*	13.00	10.90	2.80	0.22	-	0.095	0.005	0.023
M	13.70	10.70	2.68	0.22	-	0.080	-	0.015
M-1*	13.70	10.70	2.70	0.19	-	0.097	0.007	0.023
O-1	13.00	11.20	2.70	0.21	-	0.091	0.005	0.021
U	13.60	10.80	2.82	0.20	-	0.139	-	0.023
U-1*	13.10	10.20	2.60	-	-	0.088	0.007	0.023
AA**	12.80	10.00	2.56	<0.5	0.07	0.112	-	-
AA-1**	13.60	11.00	2.90	0.20	-	0.108	0.008	0.025

*Specimens had low tensile elongation: 1.4 - 2.8%

** Specimens had high yield strength: above 190 ksi

TABLE IV

Tensile Properties (70F) of Pancake Forging DGT-2 After Interim 1450F Heat Treatment and Age



Location	Heat Treatment	U. T. S.	Y.S. (0.2%)	Y.S. (0.02%)	Elong.	R.A.
BB	1450F(1) AC ± 900F(96) AC	196.8 ksi	183.5 ksi	164.2 ksi	1.2%	5.4%
BB-1*	"	203.5	191.0	169.6	1.2	6.0
CC	"	197.8	185.0	179.2	1.2	4.4
CC-1	"	191.8	178.0	162.8	1.2	6.2
DD	"	194.4	181.4	165.4	1.2	5.6
DD-1	"	195.0	181.2	169.0	1.2	5.2
NN	"	193.4	182.0	169.6	1.2	3.2
NN-1	"	191.4	181.0	169.6	4.0	4.4
OO	"	193.2	181.4	170.6	2.8	11.2
OO-1	"	193.6	182.2	174.8	1.2	9.0
PP	"	192.9	184.2	170.6	1.2	3.5
PP-1	"	195.5	185.0	180.0	1.2	6.2
ZZ	"	203.0	188.6	182.6	1.2	4.8
ZZ-1	"	202.8	188.6	178.2	1.2	3.2
AAA	"	196.6	181.5	166.8	1.2	3.2
AAA-1	"	197.8	183.2	171.5	1.2	4.8
BBB	"	207.8	195.4	182.8	2.8	6.2
BBB-1	"	205.8	193.5	180.2	1.2	5.4

*Dash 1 specimens located behind those shown in the sketch

TABLE V

Ladish Acceptance Test Compositions of Material From Three Metal Suppliers

Supplier	Heat No.	V	Cr	Al	Fe	C	H	N	O
A	A-1	13.59%	11.54	3.43	0.30	0.034	0.003	0.043	0.08
	A-2	13.38	11.68	3.14	0.30	0.021	0.002	0.020	0.12
	A-3	13.29	11.27	3.32	0.36	0.016	0.005	0.027	0.10
	A-4	13.27	11.16	3.32	0.26	0.034	0.005	0.029	0.09
	A-5	13.18	11.39	3.21	0.34	0.019	0.002	0.024	0.05
	Average	13.34	11.41	3.28	0.31	0.025	0.003	0.029	0.09
B	B-1	13.64	10.67	2.92	0.24	0.014	0.013	0.021	0.13
	B-2	13.64	11.15	3.49	0.30	0.015	0.004	0.016	0.12
	B-3	13.61	11.15	3.63	0.27	0.013	0.008	0.020	0.10
	B-4	13.61	11.65	3.36	0.38	0.015	0.003	0.021	0.10
	Average	13.63	11.16	3.35	0.30	0.014	0.005	0.020	0.11
C	C-1	13.69	10.55	3.32	0.23	0.028	0.003	0.015	0.09
	C-2	13.72	10.75	3.19	0.25	0.044	0.002	0.020	0.09
	C-3	13.25	10.53	3.22	0.16	0.066	0.002	0.021	0.09
	C-4	13.35	10.38	3.27	0.22	0.030	0.002	0.012	0.10
	C-5	13.03	10.88	3.53	0.34	0.021	0.003	0.020	0.06
	C-6	12.94	10.61	3.69	0.26	0.030	0.003	0.018	0.12
	Average	13.33	10.62	3.37	0.24	0.037	0.002	0.018	0.09
PWA Spec. 1200		12.50 - 14.50	10.00 - 12.00	2.50 - 4.00	0.30 max.	0.10 max.	0.015 max.	0.05 max.	0.20 max.

TABLE VI

Ladish Acceptance Test Tensile Properties (70F) of Material From Three Metal Suppliers

Supplier	Heat No.	T.S.	Y.S. (0.2%)	Elong.	R.A.
A	A-1	197.0 ksi	183.3 ksi	10.0%	30.5%
	"	196.2	183.0	10.5	30.5
	A-2	192.0	175.5	10.0	28.0
	"	190.5	177.3	10.0	27.3
	A-3	185.8	174.4	10.5	27.9
	"	190.0	177.0	10.0	22.1
	A-4	196.4	182.6	9.0	22.4
	"	196.3	184.4	8.5	23.3
	Average	193.0	179.7	9.8	26.5
B	B-3	212.3	198.5	6.0	13.5
	"	208.3	195.5	2.0	6.7
	"	208.0	198.0	7.5	19.1
	"	202.7	191.4	7.5	18.3
	Average	207.8	195.5	5.8	14.4
C	C-1	191.5	178.3	12.0	28.8
	"	184.2	171.9	9.5	21.5
	C-2	195.5	185.5	8.0	15.6
	"	197.1	186.5	8.0	17.8
	C-3	195.6	184.0	8.5	21.9
	"	194.4	181.9	9.5	25.9
	"	197.2	186.3	9.0	21.5
	"	194.0	185.5	7.0	19.6
	C-4	203.7	192.9	7.5	15.4
	"	204.5	194.6	5.0	14.2
	"	195.6	181.9	8.0	22.6
	"	191.5	177.8	10.0	16.9
	C-5	217.2	200.5	7.0	7.5
	"	214.1	203.0	7.0	15.4
	C-6	214.7	203.7	6.0	12.7
	"	215.8	205.9	7.0	10.1
	Average	200.4	189.0	8.1	18.6

TABLE VII

Forging Procedures for Wyman-Gordon Interstitial Pancakes

DYM-I, DYN-I, and DYO-I

	First Upset						Second Upset	
Pancake	Billet Size	Furnace Soak Treatment	Part Start Temp.	Strain* Rate	Part Finish Temp.	Part Size	Furnace Temp.	Pancake Size
DYM-1	3 1/4" dia.	1700F(2.5)AC	1650F	144"/min.	1605F	8"dia.	1400F	11.5"dia.
	8 1/4" length	to 1650F				1 1/4" thick		0.59" thick
DYN-1	3 1/4" dia.	1700F(2.5)AC	1580F	–	1650F	6 3/4" dia.	1400F	11.75" dia.
	8 1/4" length	to 1580F				1 7/8" thick		0.70" thick
DYO-1	3 1/4" dia.	1700F(2.5)AC	1580F	204	1660F	8"dia.	1400F	12" dia.
	8 1/4" length	to 1580F				1 1/4" thick		0.62" thick

*As measured by rate of head travel

TABLE VIII

Fracture Toughness (Gc)* Test Results on B-120 Pershing
Flow-Turned Cylinders Nos. 1 and 2 (40" Diame

Cylinder No.	Direction	Age	Average ** Tensile Yield Strength(0.2%)	Net Section Stress	G_c
1	axial	850F(1/2) AC	181.1 ksi	107.0 ksi	625 in lbs/in^2
"	"	"		115.0	681
"	circumferential	"	190.8	75.8	297
"	"	"		78.5	327
2	axial	"	185.4	96.5	498
"	axial	"		135.5	962
"	circumferential	"	189.3	73.5	319
"	axial	850F(1/2) AC + 800F(1) AC	191.5	77.3	315
"	"	"		73.0	280
"	circumferential	"	200.4	61.6	203
"	axial	850F(1/2) AC + 800F(2) AC	205.0	63.6	218
"	"	"		67.8	247
"	circumferential	"	224.3	59.0	181

*3"x12" internally notched specimen used
**average of two results

TABLE IX

Modified Charpy Impact Test Results on Pershing Flow-Turned Cylinders Nos. 1 and 2 at 70F and -35F

Cylinder No.	Test Temperature	Direction	Age	Tensile* Yield Strength(0.2%)	Energy Absorption
1	70F	axial	850F(1/2) AC	181.2 ksi	1.2 ft-lbs
"	"	"	"	"	-
"	"	circumferential	"	190.0	2.8
"	"	"	"	"	1.6
"	-35F	axial	"	181.2	1.3
"	"	"	"	"	1.3
"	"	circumferential	"	190.0	1.3
"	"	"	"	"	1.8
2	70F	axial	"	185.4	2.0
"	"	"	"	"	1.2
"	"	"	"	"	2.0
"	"	circumferential	"	189.3	1.2
"	"	"	"	"	2.3
"	"	"	"	"	1.0
	"	axial	850(1/2) AC +800F (1) AC	200.4	1.2
"	"	"	"	"	1.2
"	"	"		"	1.0
"	"	circumferential	"	207.6	0.8
"	"	"		"	1.5
"	"	"	"	"	1.5
"	"	axial	850F(1/2) AC +800F(2) AC	205.0	1.3
"	"	"	"	"	1.3
"	"	"	"	"	1.0
"		circumferential	"	224.3	2.0
"	"	"	"	"	2.0
"	"	"	"	"	1.3
"	-35F	axial	850F(1/2) AC	185.4	1.5
"	"	circumferential	"	189.3	1.3
"	"	axial	850F(1/2) AC +800F(1) AC	200.4	1.0
	"	"	"	"	1.3
"	"	"	850F(1/2) AC +800F(2) AC	205.0	1.5
"	"	circumferential	"	224.3	1.0
"	"	"	"	"	1.0

*all values determined at 70F

TABLE X

Tensile Properties (70F) of Cold-Rolled and Flow-Turned Material with Respect to Direction and Thickness

1. Cold-Rolled Material*

Direction	Age	Test Area	T.S.	Y.S. (0.2%)	Elong.
longitudinal	800F(1) AC	total thickness	184.0 ksi	178.0 ksi	8.0%
"	"	"	187.7	181.0	8.0
"	800F(2) AC	"	193.0	187.0	7.0
"	"	"	188.0	180.0	9.0
"	800F(4) AC	"	233.0	225.0	3.0
"	"	"	210.0	202.0	7.0
transverse	800F(1) AC	"	195.0	182.5	6.0
"	"	"	196.0	182.0	6.0
"	800F(2) AC	"	195.5	187.5	5.0
"	"	"	197.0	186.0	4.0
"	800F(4) AC	"	215.0	204.5	5.0
"	"	"	216.0	204.0	5.0

2. Flow-Turned Material**

Direction	Age	Test Area	T.S.	Y.S. (0.2%)	Elong.
axial	850F(1/2) AC	total thickness	187.5	180.5	6.5
"	"	"	187.0	181.8	5.0
circumferential	"	"	199.0	190.0	5.5
"	"	"	204.8	-	5.5
"	"	outside half of wall thickness	208.8	202.0	2.5
"	"	"	193.8	190.2	3.0
axial	"	inside half of wall thickness	192.8	187.6	4.0
"	"	"	188.2	182.0	3.5
circumferential	"	"	177.4	176.0	5.0
"	"	"	184.6	178.8	3.5

*Cold-rolled to fifty per cent reduction in multiple passes

** Flow-turned to fifty per cent reduction in single pass

TABLE XI

Tensile Properties (70F) and Bend Test Results on B-120VCA TIG and Electron-Beam Welds

Panel No.	Material	Weld Process	T.S.	Y.S. (0.2%)	Elong.	Failure	Bend Dia.	Bend Angle
C1(1)	mill annealed (0.125" thick)	TIG(3)	130.3 ksi	127.6 ksi	12.0%	weld	7.1T	34°
C3(1)	"	"	125.5	122.4	6.0	weld	9.0	43
C4(2)	"	"	138.6	136.2	10.0	heat affected zone	9.0	135
C6(2)	"	"	138.8	134.2	12.0	heat affected zone	9.0	147
356 (2)	"	electron(5) beam	137.0	136.2	5.0	weld	6.3	20
357 (2)	cold rolled(4) and aged (0.085" thick)	"	154.2	150.0	3.0	weld	8.1	144
358 (2)	"	"	149.8	148.6	5.0	weld	5.6	140

(1) Tested with weld bead ground flush and transversely centered in gage length.

(2) Tested with weld bead intact and transversely centered in gage length.

(3) Welded using B-120VCA filler wire.

(4) Reduced 35% by cold rolling and aged at 800F for 4 hours prior to welding.

(5) Welded without filler material.

TABLE XII

Fracture Toughness (G_c) Test Results on B-120 VCA TIG and Electron-Beam Welds

Panel No.	Specimen Size	Material	Weld[1] Process	Net Section stress	G_c	N.T.S. (K_t=18)
		mill annealed				
N-1[2]	3"x12"	(0.125" thick)	TIG	60.6 ksi	216 in lbs/in^2	-
N-2[2]		"	"	49.0	136	-
N-3[2]		"	"	56.7	183	-
N-4[2]			"	56.2	172	-
			Average	55.4	177	-
		mill annealed				
C-1	3"x12"	(0.125" thick)	TIG	126.5	1480	-
C3		"	"	52.5	155	-
C4		"	"	77.5	338	-
C6		"	"	55.0	164	-
			Average	77.9	534	-
		mill annealed	electron			
360[3]	1"x4"	(0.125" thick)	beam	153.0	560	123.0 ksi
361[3]		"	"	121.0	330	110.8
362[3]		"	"	152.0	535	140.0
			Average	142.0	475	124.3
		cold rolled and[4]	electron			
356[3]	1"x4"	age (0.085" thick)	beam	171.0	>1290	146.0
357[3]		"	"	140.0	490	140.0
"		"	"	155.0	625	138.5
358[3]		"	"	163.0	>889	118.0
			Average	157.3	821	135.6
358	3"x12"	cold rolled and age (0.085" thick)	electron beam	112.0	795	

(1) TIG welding done with B-120VCA filler wire; electron beam welding (Hamilton Standard) without filler material.

(2) Panels TIG welded at PWA but specimens machined and tested at Naval Research Laboratory.

(3) Specimens machined to Figure 22. All other specimens machined to Figure 18.

(4) Reduced 35% by cold rolling, aged at 800F for 4 hours prior to welding

TABLE XIII

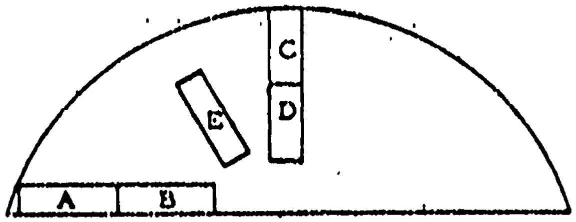
Forging Procedures for Wyman-Gordon High and Low Strain Rate Pancakes DYW-1, DYW-2, DYW-3 and DYW-4*

Pancake	Billet Size	Furnace Soak Treatment	Part Start Temp.	Strain Rate	Part Finish Temp.	Pancake Size
DYW-1	5" dia. 7 1/4" length	1700F(2.7) AC to 1600F	1600F	7.32"/min.	<1400F	15 3/4" dia. 0.76" thick.
DYW-2	5" dia. 8 1/4" length	1700F(2.6) AC to 1600F	1600	63.6	1575	15 1/2" dia. 0.84" thick.
DYW-3	5" dia. 8 1/4" length	1400F(1.5) + 1500F(1.5) + 1850F(1.8) AC to 1685F	1685	4.5	<1400	15 1/2" dia. 0.82" thick.
DYW-4	5" dia. 8 1/4" length	1400F(1.5) + 1500F(1.5) + 1850F(2) AC to 1660F	1660	76.3	1615	18" dia. 0.81" thick.

*Forged in a single upset

TABLE XIV

Wyman-Gordon Tensile Properties (70F) of High and Low Strain Rate Forgings
DYW-1, DYW-2, DYW-3, and DYW-4



1. Pancake DYW-1

Furnace Temp.	Start Temp.	Strain Rate	Finish Temp.	Age	Location	T.S.	Y.S. (0.2%)	Elong.	R.A.
1700F	1600F	7.3"/min.	< 1400F	960F(16) AC	E	192.1 ksi	178.9 ksi	5.0%	10.4%
				960F(24) AC	C	205.4	190.7	5.0	7.5
				"	D	190.9	175.0	6.0	10.3
				960F(36) AC	A	205.4	190.7	5.0	10.4
				"	B	198.9	183.6	6.0	9.3

2. Pancake DYW-2

Furnace Temp.	Start Temp.	Strain Rate	Finish Temp.	Age	Location	T.S.	Y.S. (0.2%)	Elong.	R.A.
1700	1600	63.6	1575	960F(16) AC	E	180.5	164.6	6.0	10.1
				960F(24) AC	C	193.3	177.6	4.0	8.5
				"	D	179.9	163.8	5.0	9.3
				960F(36) AC	A	201.5	183.8	4.0	6.6
				"	B	185.6	167.4	8.0	11.5

3. Pancake DYW-3

Furnace Temp.	Start Temp.	Strain Rate	Finish Temp.	Age	Location	T.S.	Y.S. (0.2%)	Elong.	R.A.
1890	1685	4.5	< 1400	960F(16) AC	E	179.3	167.2	6.0	12.8
				960F(24) AC	C	199.5	185.4	6.0	10.0
				"	D	183.3	170.7	5.0	11.0
				960F(36) AC	A	206.4	192.1	4.0	7.4
				"	B	190.1	175.4	8.0	11.2

4. Pancake DYW-4

Furnace Temp.	Start Temp.	Strain Rate	Finish Temp.	Age	Location	T.S.	Y.S. (0.2%)	Elong.	R.A.
1850	1660	76.3	1615	960F(16) AC	E	164.0	150.9	8.0	13.1
				960F(24) AC	C	190.5	175.6	4.0	8.5
				"	D	175.4	161.1	7.0	11.6
				960F(36) AC	A	199.9	183.1	6.0	8.6
				"	B	191.3	187.6	8.0	12.4

TABLE XV

Ladish Acceptance Test Tensile Properties (70F) on Heat of Material for Hammer and Roll Forgings

Ingot Location	Preparation	Heat Treatment	T.S.	Y.S (0.2%)	Elong.	R.A.
top	-	1400F(2) AC	138.6 ksi	138.6 ksi	17.0%	52.6%
"	-	"	138.2	137.0	19.0	50.1
bottom	-	"	139.6	134.0	19.5	48.1
"	"	"	135.2	133.2	18.5	47.2
top	1 1/2" sq. heated to 1600F and drawn to 1 1/4" sq.	900F(20) AC	201.9	189.4	9.0	17.1
		"	204.1	191.2	9.5	18.2
bottom	"	"	192.2	179.7	10.5	21.1
	"	"	190.2	178.6	10.5	18.3
top	1 1/2" sq. heated to 1500F and drawn to 1 3/8" sq.	"	203.7	190.1	5.5	11.6
	"		202.7	187.8	6.0	12.5
bottom	"	"	187.1	174.6	9.0	16.0
	"	"	181.0	168.9	12.0	22.1
top	upset 66% from 1900F, finish temp. 1640-1690 F, water quenched	1400F(2) AC	133.4	131.2	12.0	32.8
	"	"	135.3	133.5	15.5	36.3
	"	800F(48) AC	206.9	198.5	3.0	7.4
	"	"	200.9	190.4	2.0	8.2
bottom	upset 66% from 2000F, finish temp. 1800-1850F, water quenched	1400F(2) AC	136.3	132.3	17.5	37.6
	"	"	132.8	130.4	15.0	34.6
	"	800F(48) AC	163.7	154.9	9.0	18.9
"	"	"	160.5	153.2	7.0	14.6

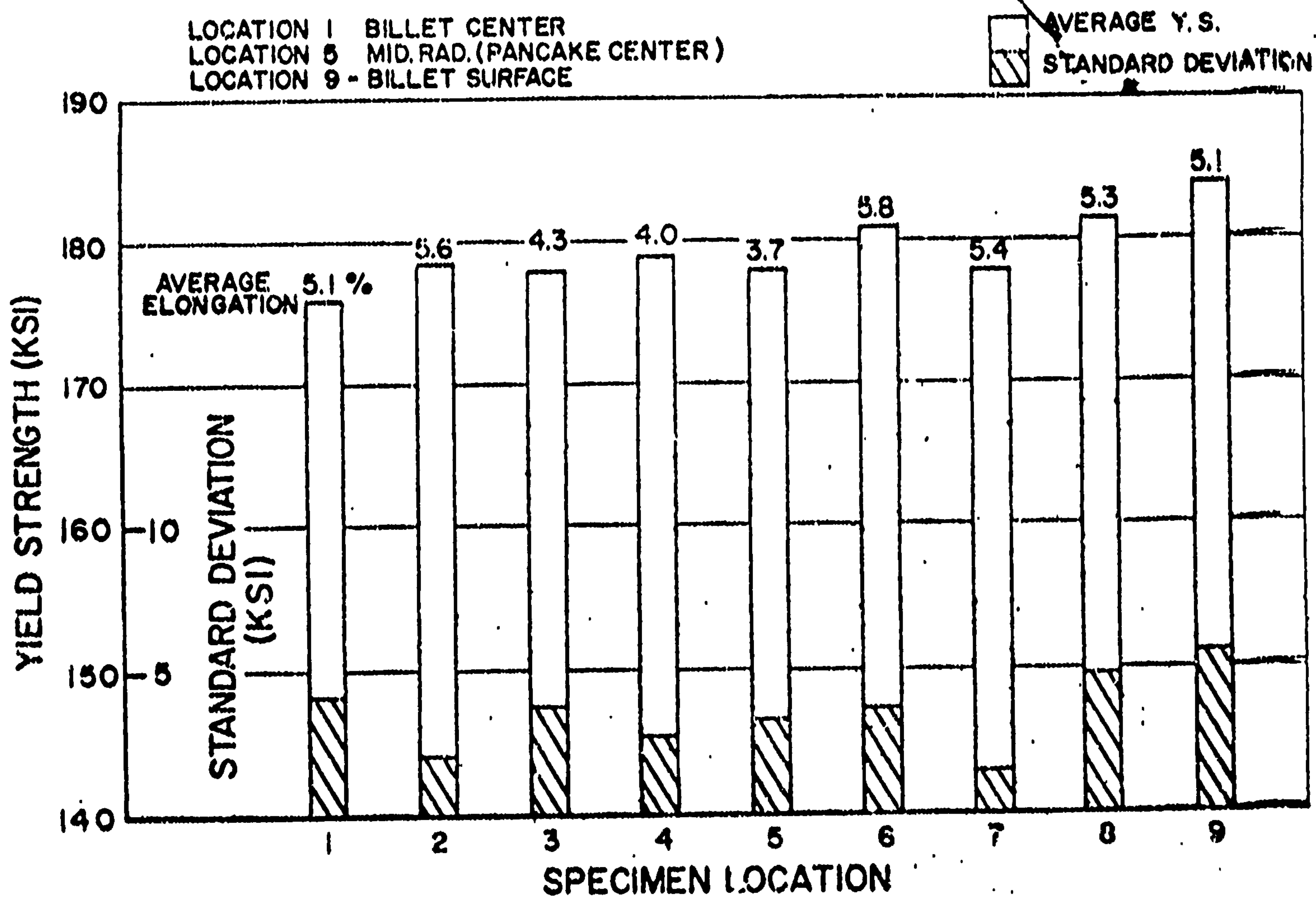
TABLE XV
(Continued)

Ingot Location	Preparation	Heat Treatment	T. S.	Y. S. (0.2%)	Elong.	R. A.
top	upset 5% from 1650F, finish temp. 1400-1450F	1400F(2) AC	139.2	137.0	16.0	48.0
"	"	"	139.1	134.9	14.0	41.3
"	"	800F(48) AC	202.0	192.5	7.5	16.0
bottom	"	1400F(2) AC	138.1	135.3	17.0	42.0
"	"	"	139.2	137.0	16.0	48.0
"	"	800F(48) AC	199.9	187.4	9.0	17.4

APPENDIX B

Figures

YIELD STRENGTH AND STANDARD DEVIATION FOR VERTICAL SECTIONS THROUGH PANCAKE DGT — 2



PRATT & WHITNEY AIRCRAFT
DIVISION OF
UNITED AIRCRAFT CORPORATION

Figure 1

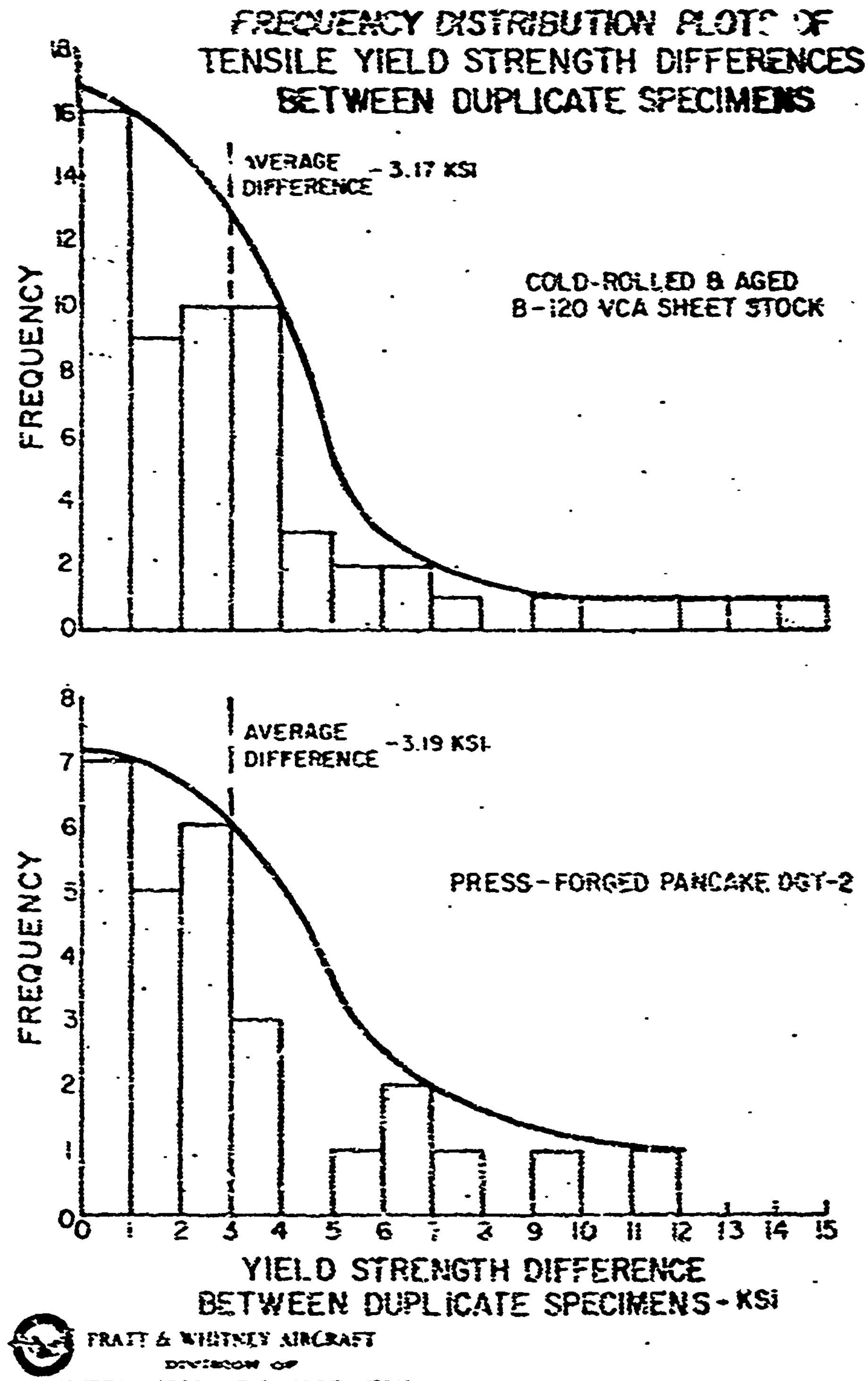
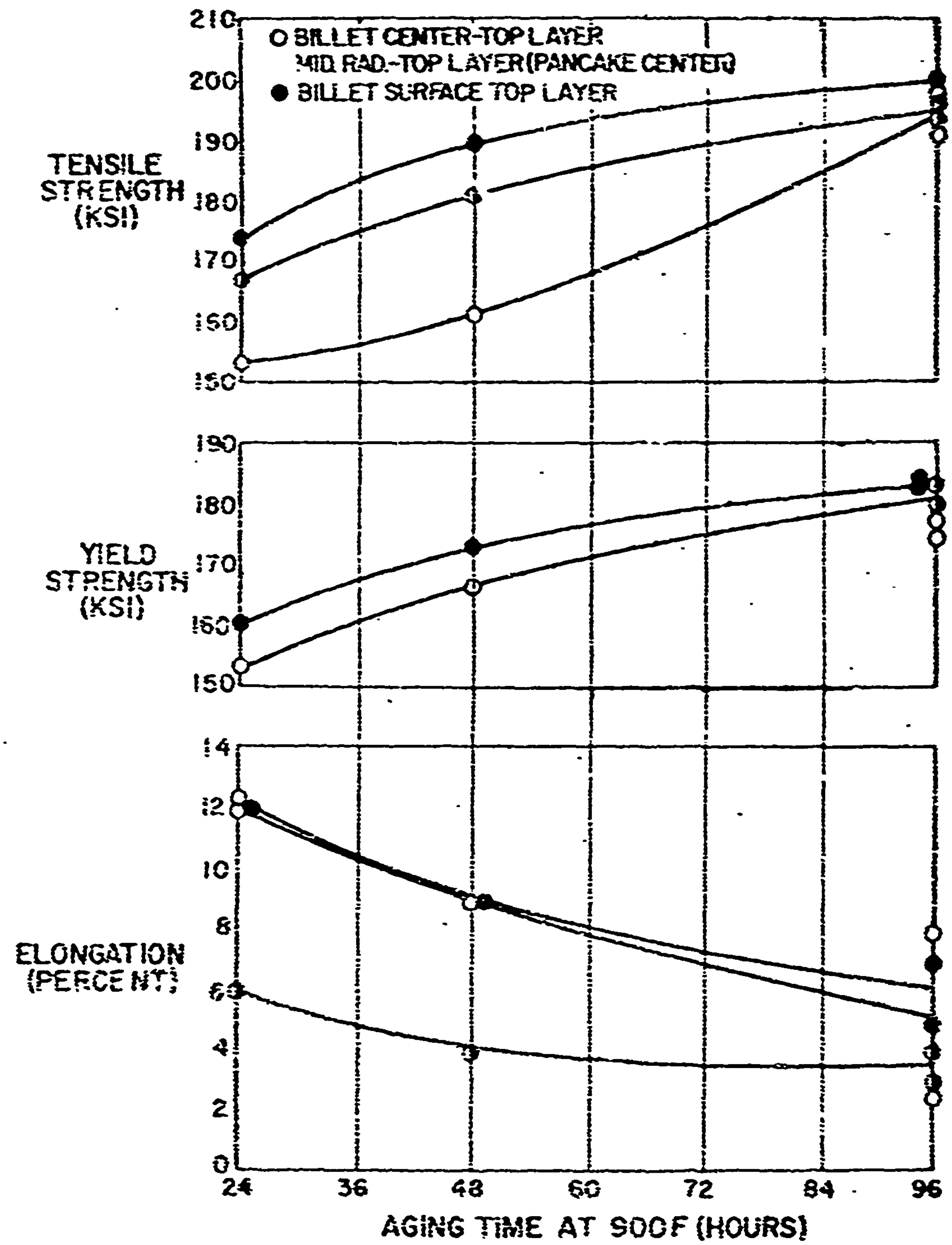

FREQUENCY DISTRIBUTION PLOTS OF
TENSILE YIELD STRENGTH DIFFERENCES
BETWEEN DUPLICATE SPECIMENS
AVERAGE DIFFERENCE - 3.17 KSI
COLD-ROLLED & AGED
B-120 VCA SHEET STOCK
FREQUENCY
AVERAGE DIFFERENCE - 3.19 KSI
PRESS-FORGED PANCAKE DGT-2
FREQUENCY
YIELD STRENGTH DIFFERENCE
BETWEEN DUPLICATE SPECIMENS - KSI
PRATT & WHITNEY AIRCRAFT
DIVISION OF
UNITED AIRCRAFT CORPORATION

Figure 2

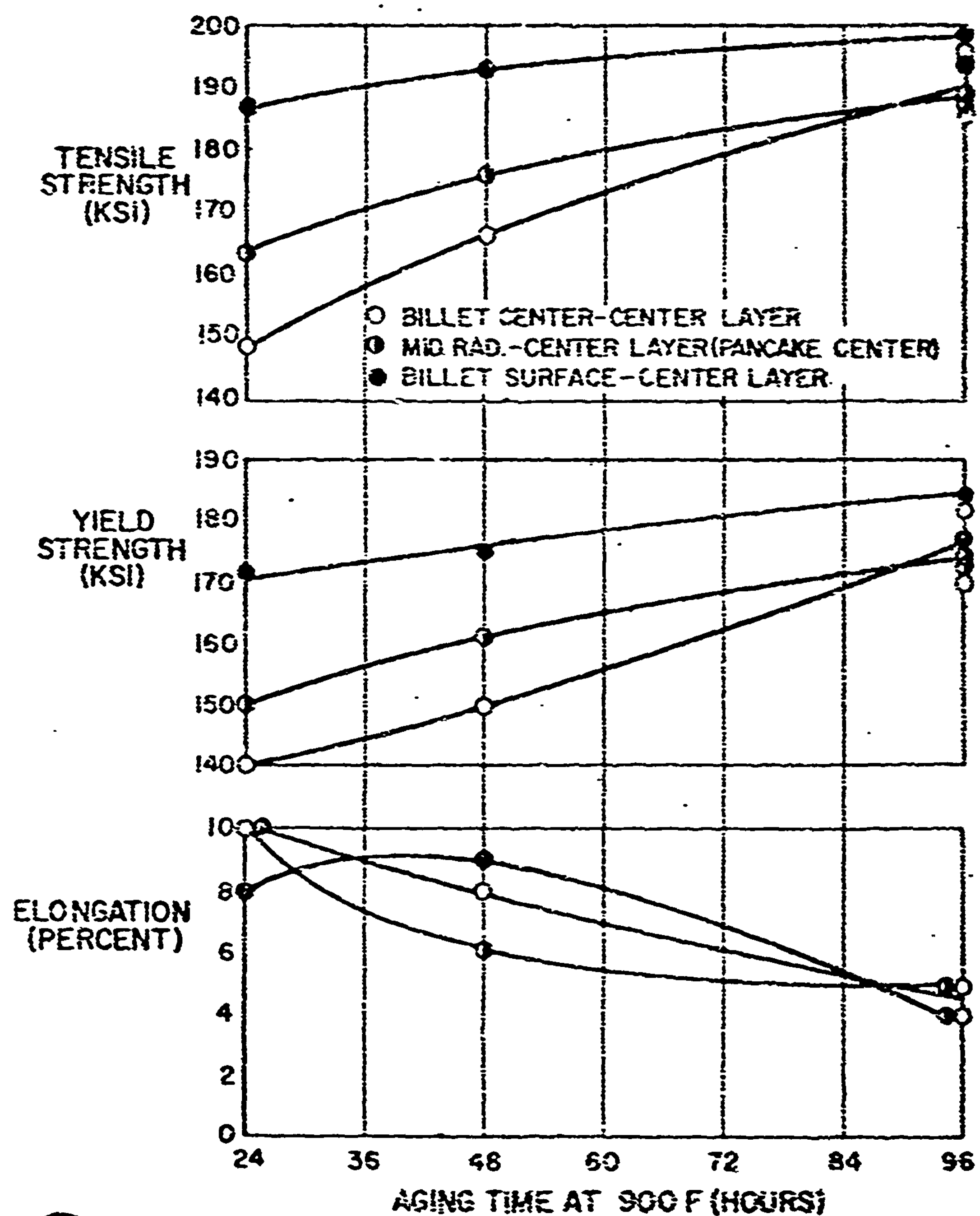
AGING CURVES FOR TOP LAYER OF PANCAKE FORGING DGT-2



PRATT & WHITNEY AIRCRAFT
DIVISION OF
UNITED AIRCRAFT CORPORATION

Figure 3

AGING CURVES FOR CENTER LAYER OF PANCAKE FORGING DGT-2

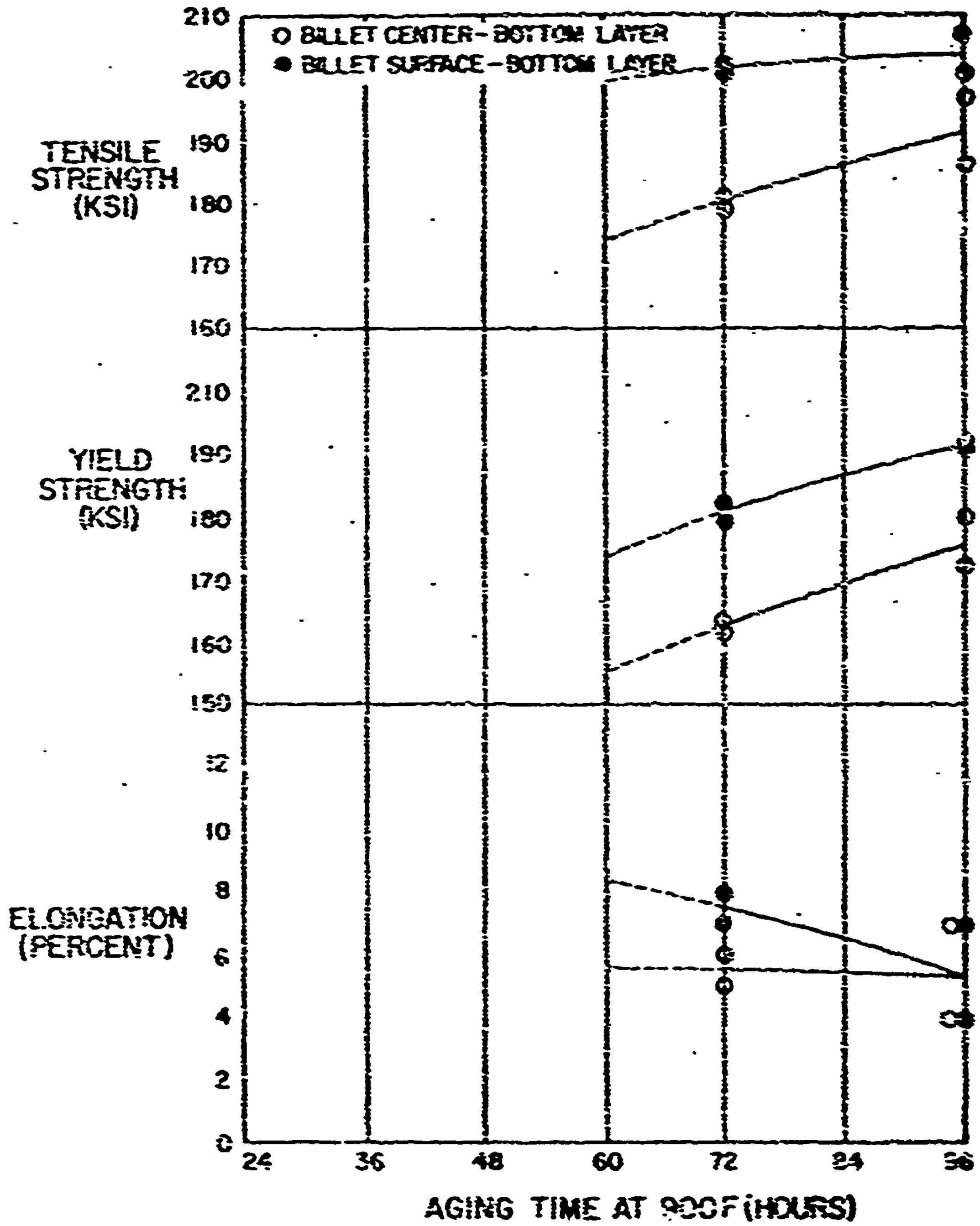


PRATT & WHITNEY AIRCRAFT
DIVISION OF
UNITED AIRCRAFT CORPORATION

3-25-41

Figure 4

AGING CURVES FOR BOTTOM LAYER OF PANCAKE FORGING DGT-2



PRATT & WHITNEY AIRCRAFT
DIVISION OF
UNITED AIRCRAFT CORPORATION

Figure 5

YIELD STRENGTHS FOR VERTICAL SECTIONS THROUGH PANCAKE FORGING DGT-2 AFTER AGING AT 900F FOR 24-96 HOURS

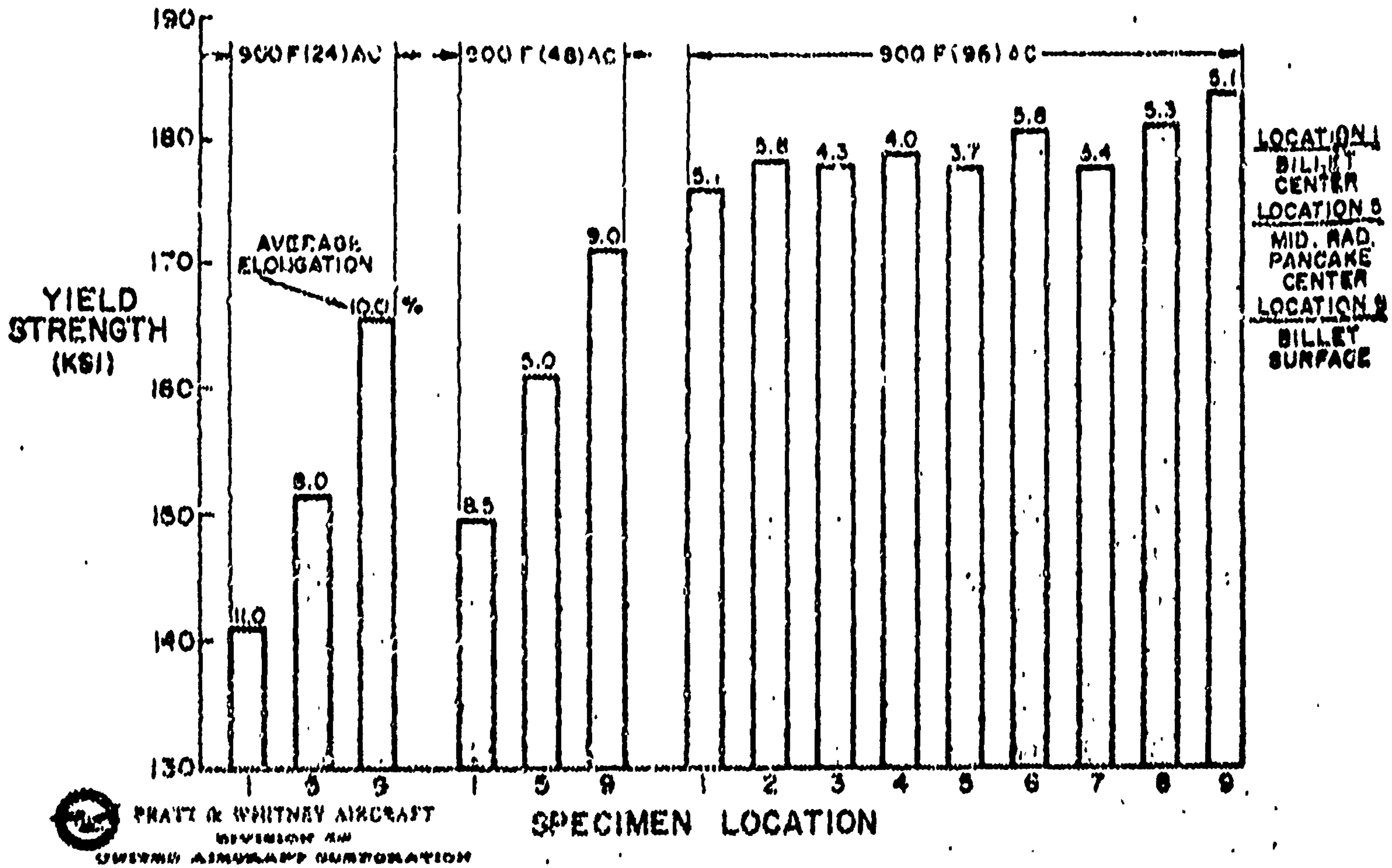
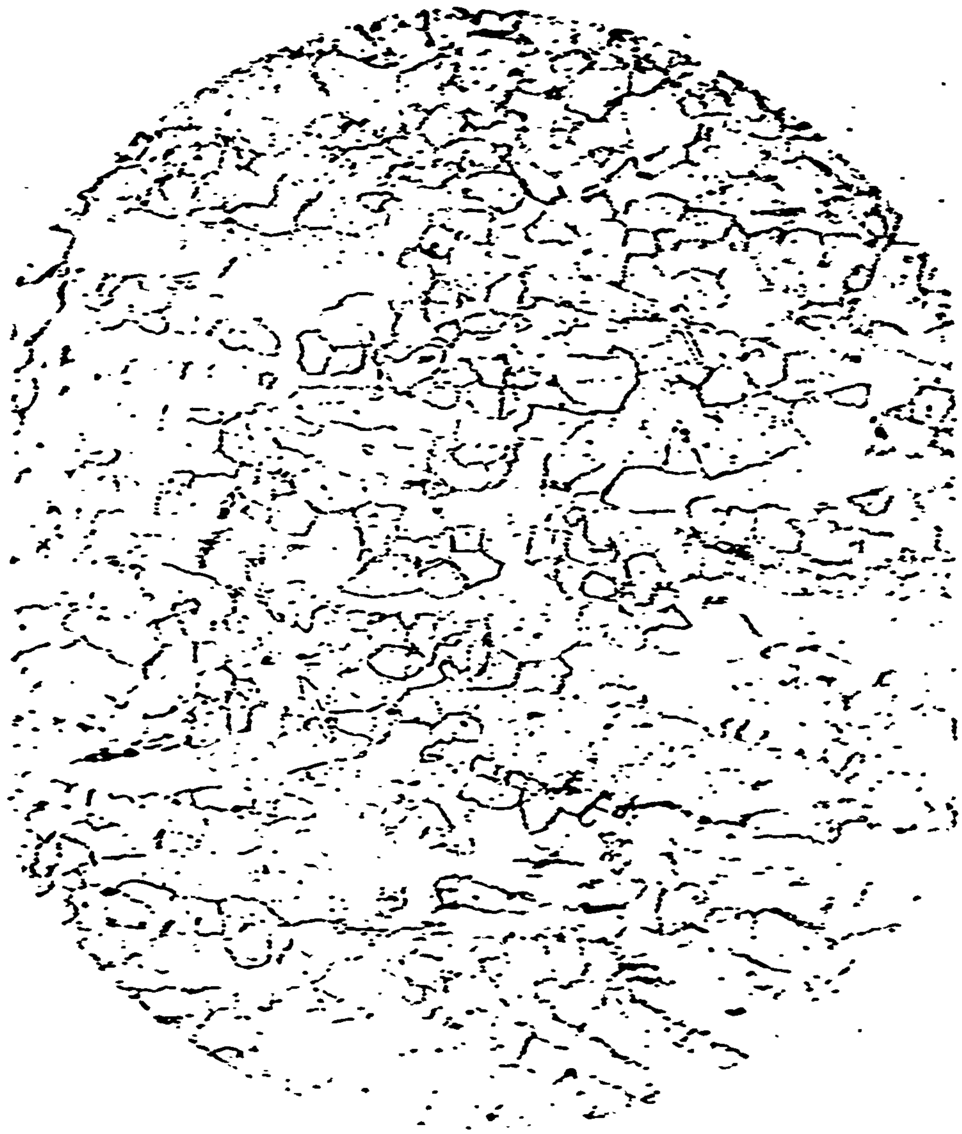


Figure 6



ETCHANT: 5% HF, 35% HNO_3 MAG: 100X
MICROSTRUCTURE NEAR BILLET SURFACE OF PANCAKE DGT-2 SHOWING RESIDUAL COLD WORK (ARROWS).

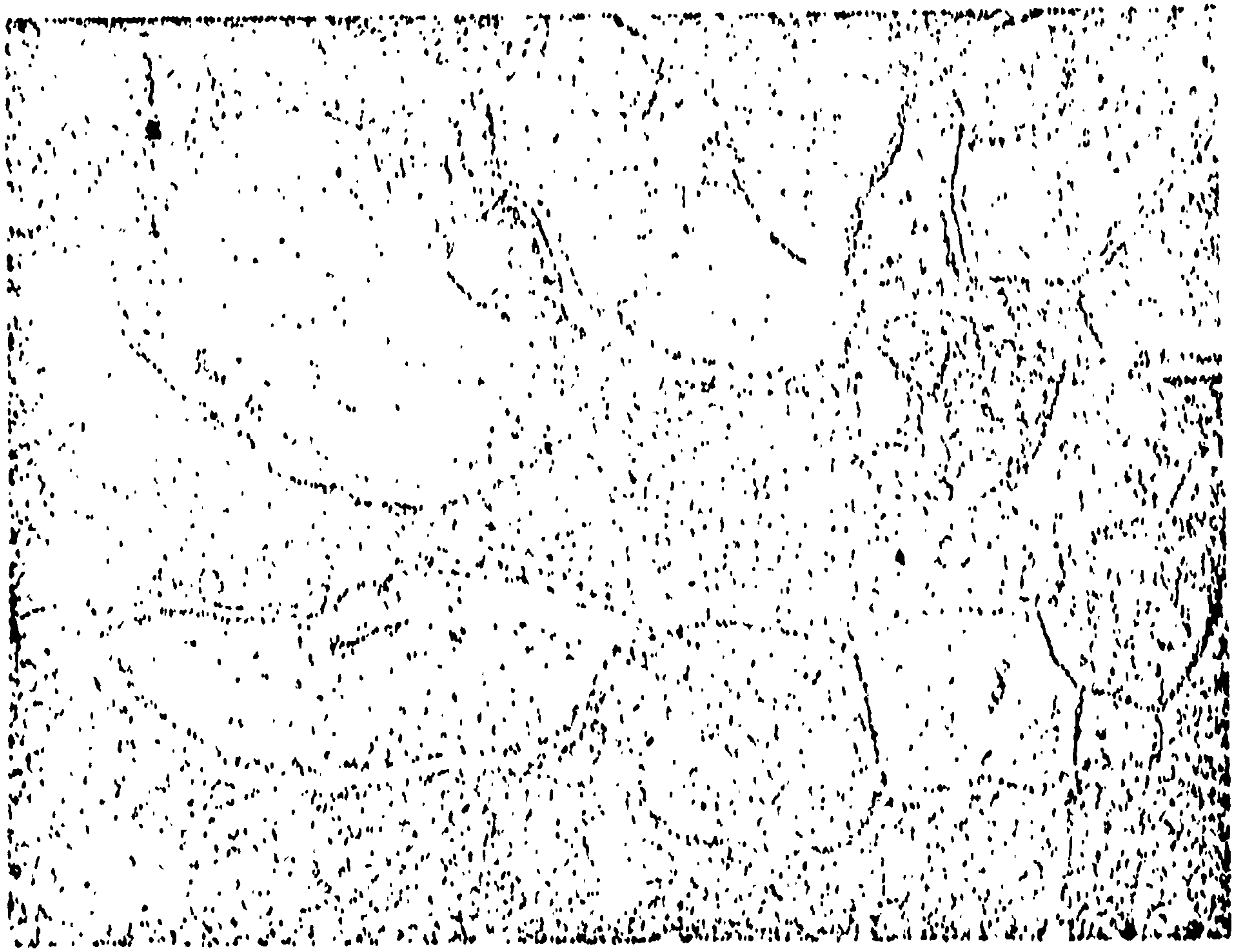
H-15054-3

Figure 7

ETCHANT: 5% HF, 35% HNO_3 MAG: 100X
MICROSTRUCTURE NEAR ORIGINAL BILLET CENTER OF PANCAKE DG7-2. STRUCTURE SIMILAR TO THAT NEAR BILLET SURFACE BUT WITHOUT INDICATIONS OF COLD WORK.

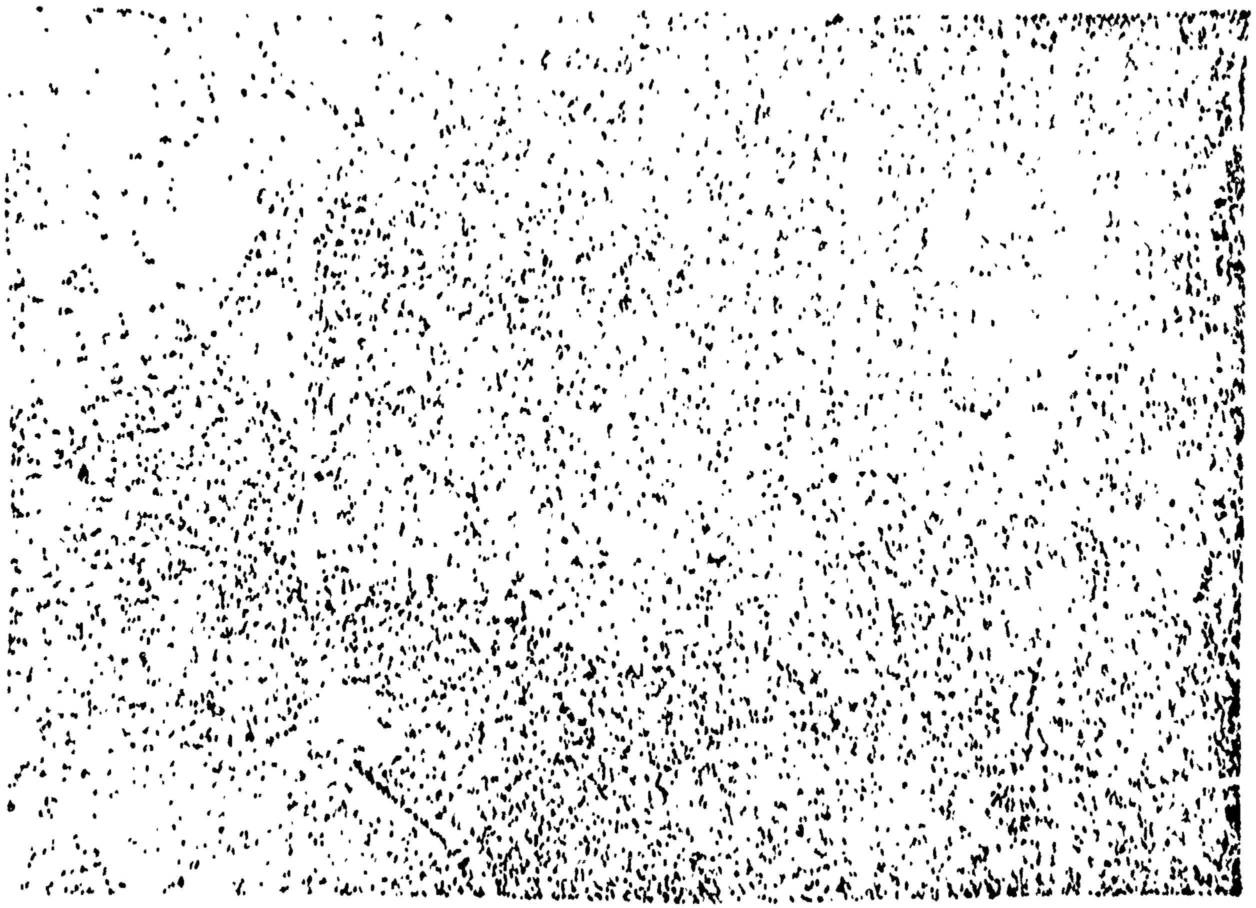
H-11850-25

Figure 8



ETCHANTS 5% HF, 35% HNO_3 MAG: 500X
MICROSTRUCTURE OF TENSILE SPECIMEN FROM LOCATION B, PANCAKE DCT-2, AGED AT 900F. FOR 96 HRS. YIELD STRENGTH 170.5 KSI.
NOTE RELATIVELY COARSE AGING PRECIPITATE.
H-15173-96

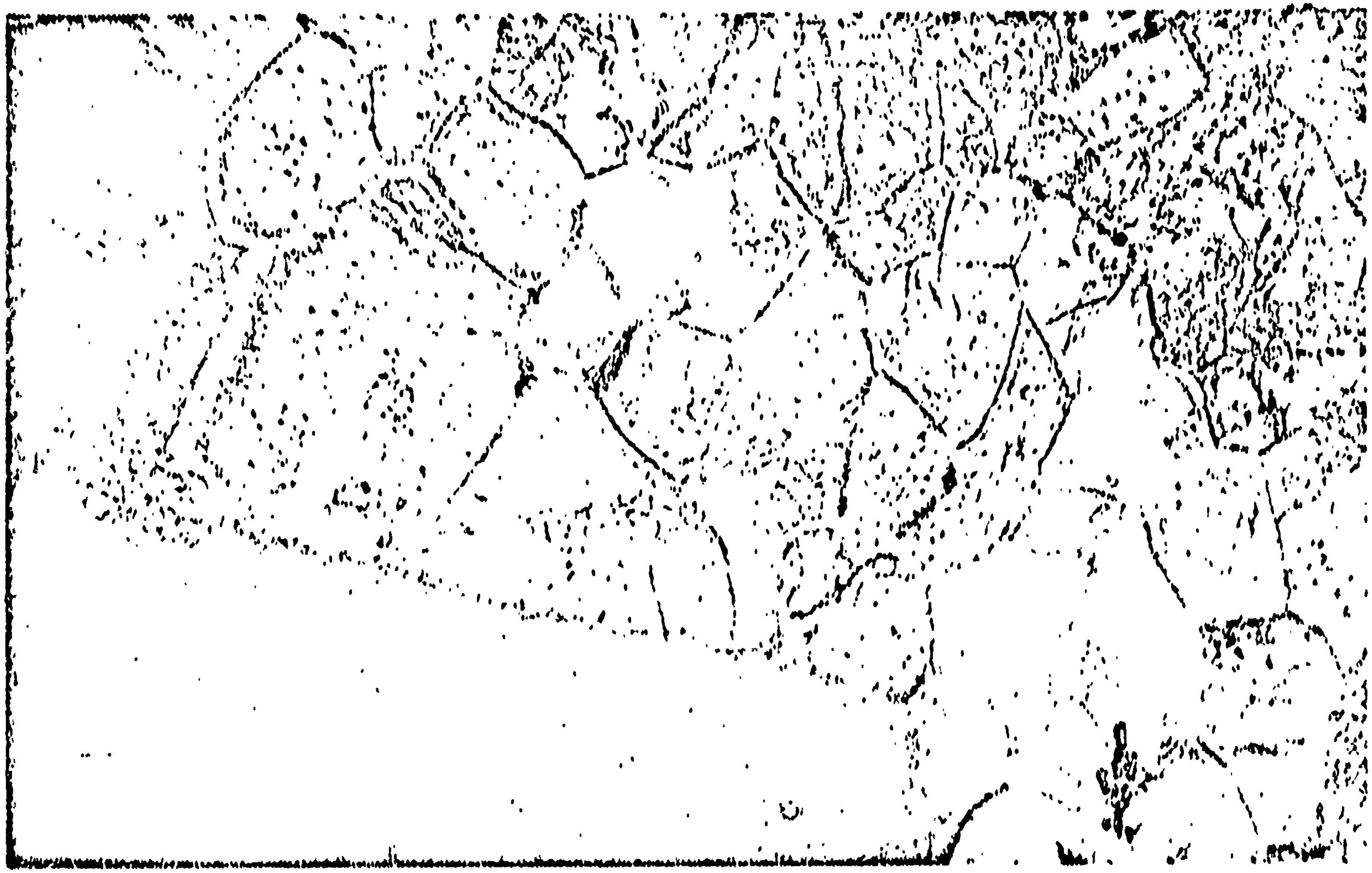
Figure 9



ETCHANT: 5% HF, 35% HNO3 MAG: 500X
MICROSTRUCTURE OF TENSILE SPECIMEN FROM LOCATION AA, PANCAKE DOT-2. AGED AT 900F FOR 96 HRS. YIELD STRENGTH 132.0 KSI. NOTE RELATIVELY FINE DISTRIBUTION OF AGING CONSTITUENT.

H-16782-30

Figure 18



ETCHANT: 5% HF, 35 HNO_3 MAG: 500X
MICROSTRUCTURE AT FRACTURE SURFACE OF TENSILE SPECIMEN FROM PANCAKE DQT-2 (LOCATION O) WHICH SHOWED LOW (2.4%) ELONGATION AFTER AGING AT 900F FOR 96 HRS. NOTE PARTIALLY INTERGRANULAR FAILURE

H-18089-24

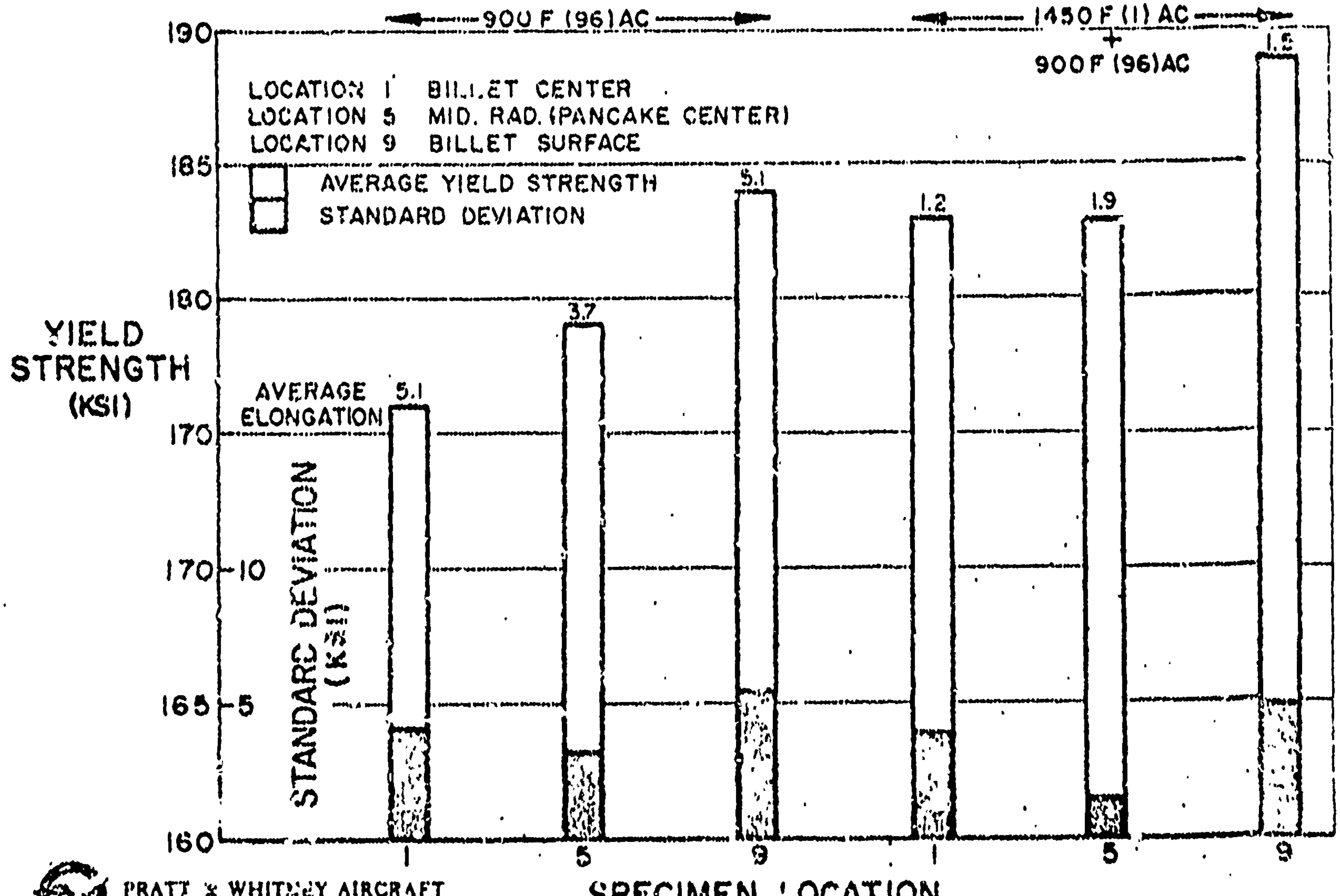
Figure 11

ETCHANT: 5% HF, 35 HNO_3 MAG: 500X
MICROSTRUCTURE AT FRACTURE SURFACE OF TENSILE SPECIMEN FROM PANCAKE DGT-2 (LOCATION U) WHICH SHOWED SATISFACTORY (6.8%) ELONGATION AFTER AGING AT 900F FOR 96 HRS. NOTE MOSTLY TRANSGRANULAR FAILURE

H-16049-32

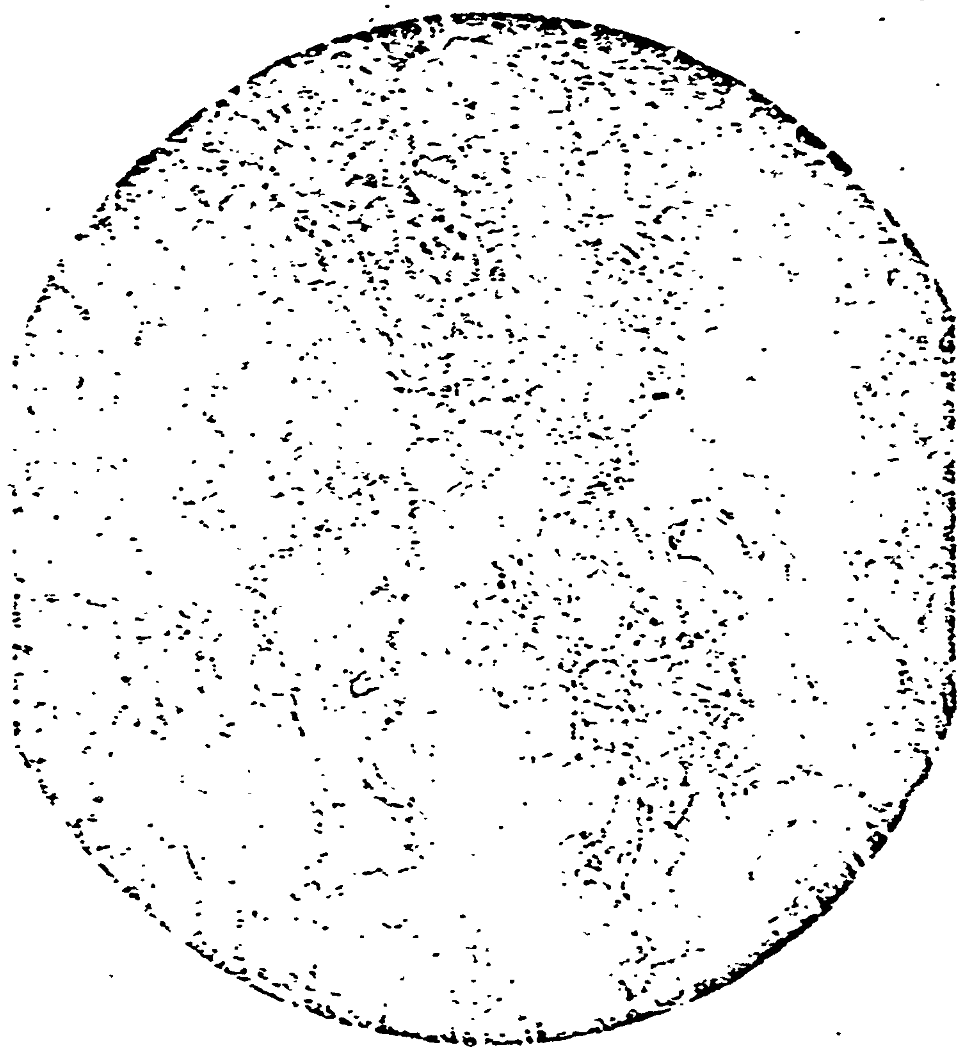
Figure 12

YIELD STRENGTHS & STANDARD DEVIATIONS FOR VERTICAL SECTIONS THROUGH PANCAKE DGT-2 AFTER 900 F (96) AC & 1450 F (1) AC + 900 F (96) AC HEAT TREATMENTS



PRATT & WHITNEY AIRCRAFT
DIVISION OF
UNITED AIRCRAFT CORPORATION

Figure 13

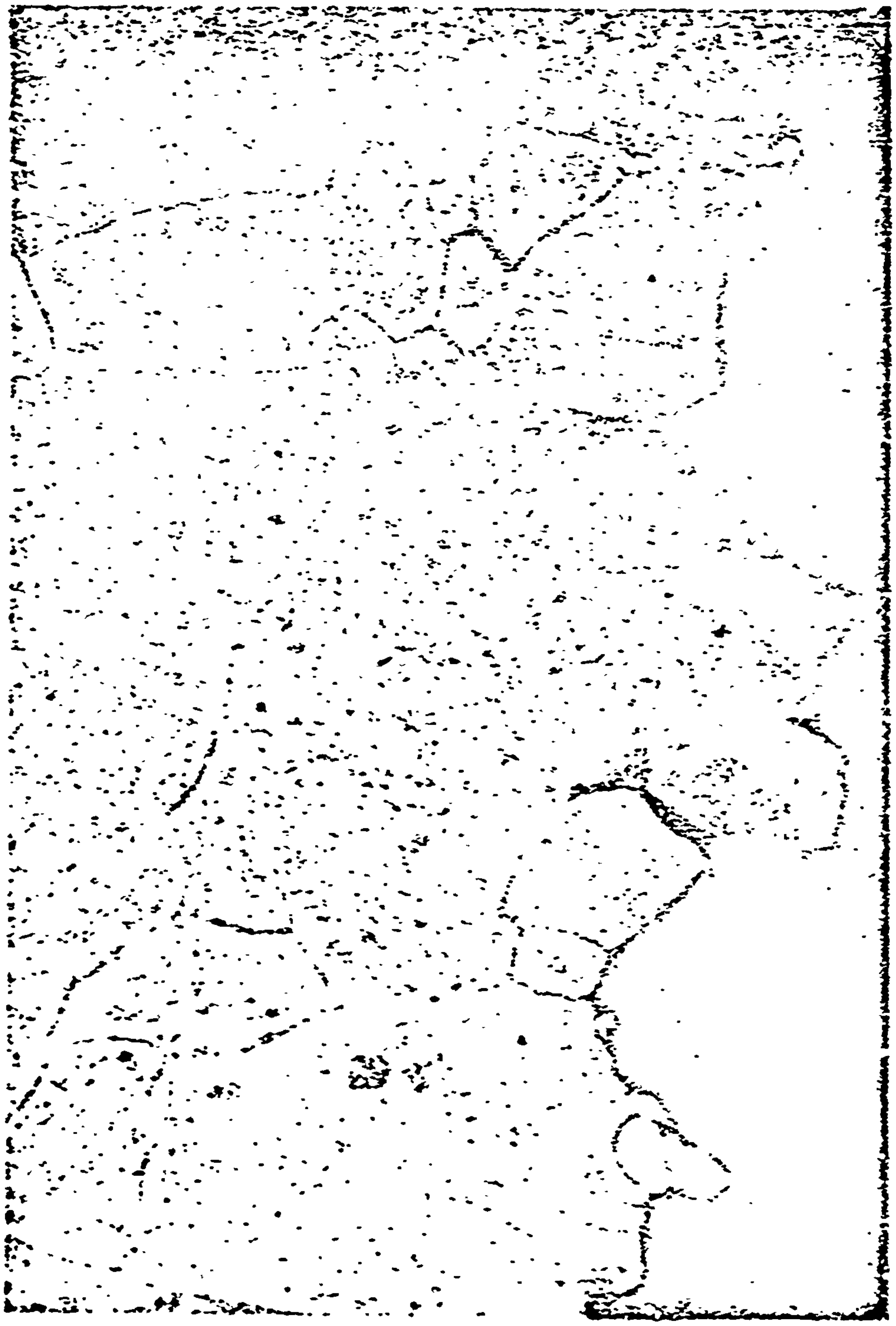


ETCHANT: 5% HF, 35% HNO_3 MAG: 100X

TYPICAL MICROSTRUCTURE OF PANCAKE DGT-2 AFTER HEAT TREATMENT AT 1450F FOR ONE HOUR AND AGING AT 900F FOR 96 HRS

H-15490-64

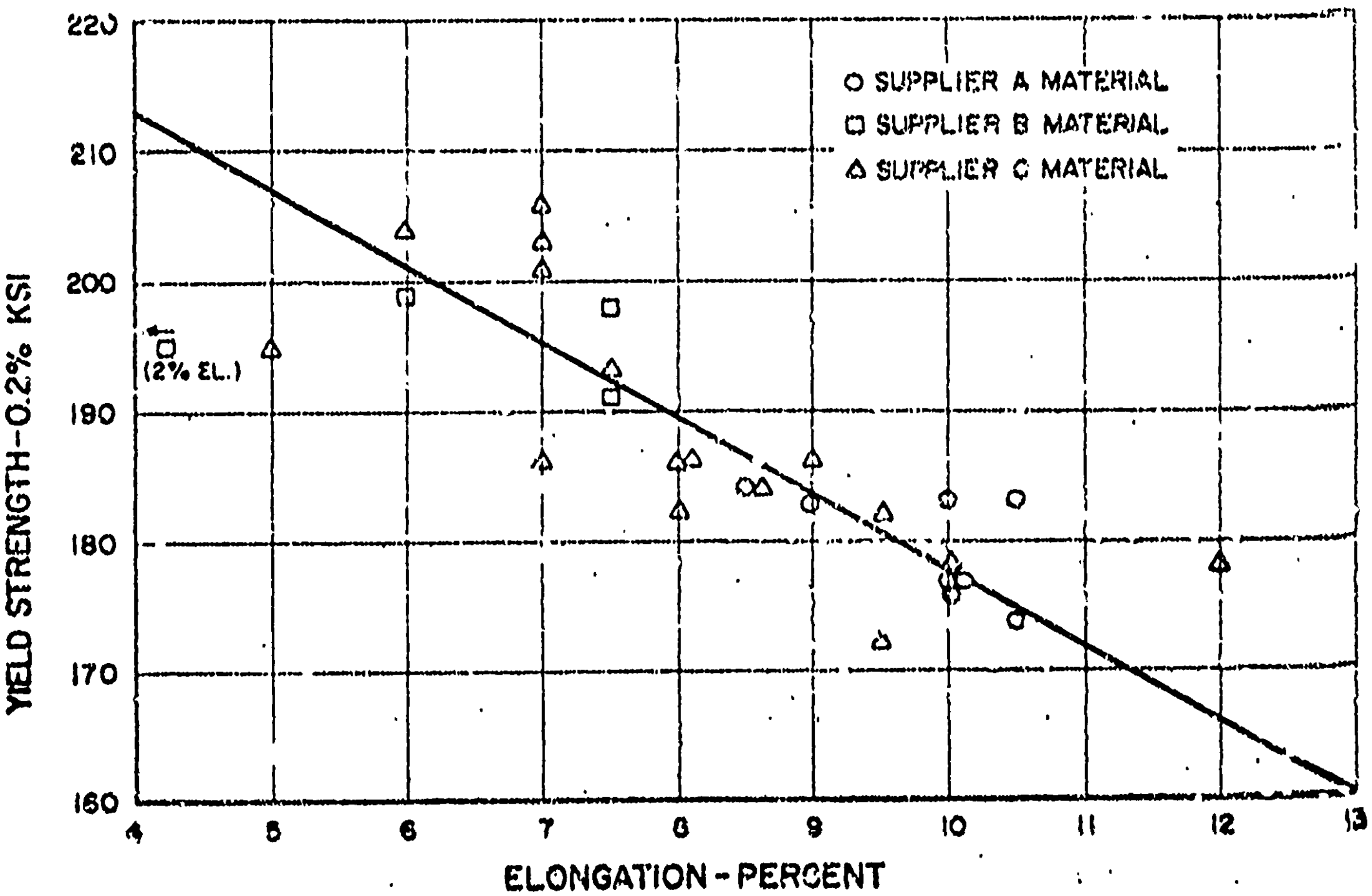
Figure 14



ETCHANT: 5% HF, 35% HNO_3 MAG: 500X
MICROSTRUCTURE AT FRACTURE SURFACE OF TENSILE SPECIMEN FROM PANCAKE DCT-2 AFTER 1850F HEAT TREATMENT AND AGE. SPECIMEN HAD 1.2% ELONGATION. NOTE INTERGRANULAR FAILURE.
H-16419-25

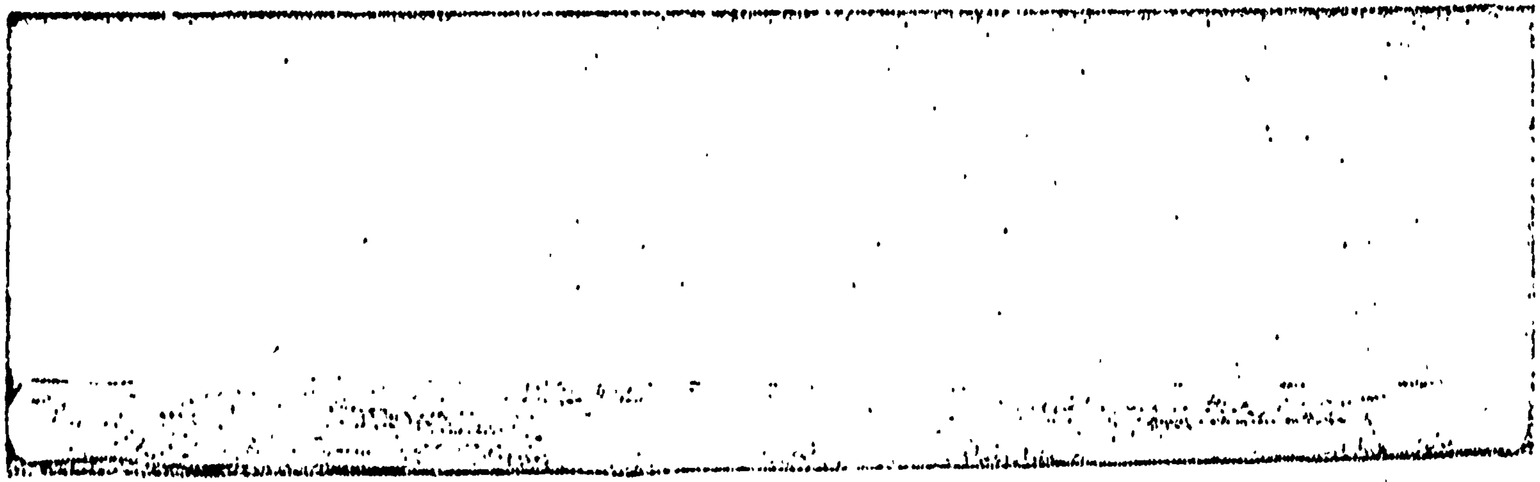
Figure 15

YIELD STRENGTH VS. ELONGATION FOR MATERIAL FROM SUPPLIERS A, B AND C AS DETERMINED BY LADISH COMPANY ACCEPTANCE TESTING



PRATT & WHITNEY AIRCRAFT
DIVISION OF
UNITED AIRCRAFT CORPORATION

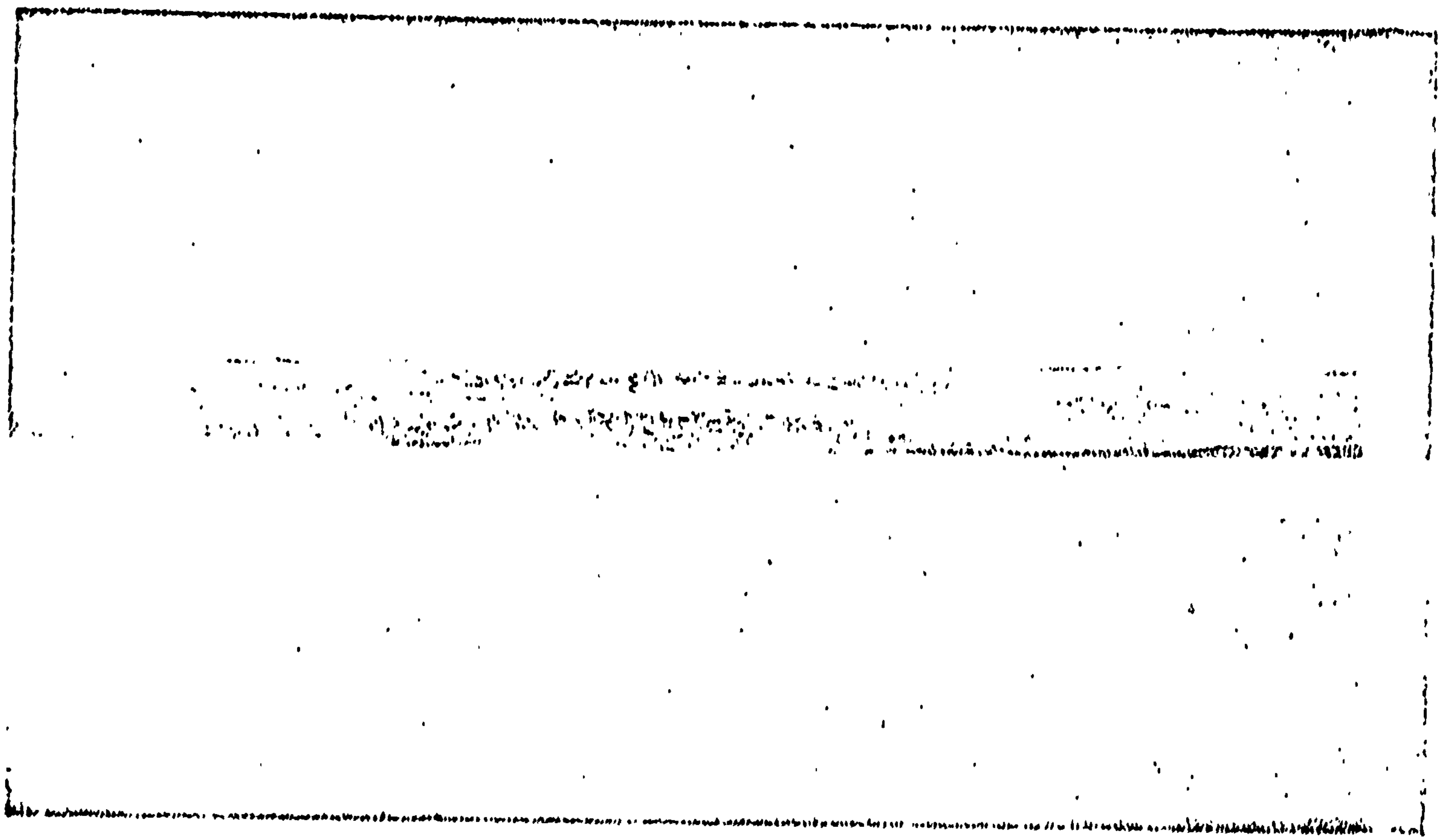
Figure 36



ETCHANT: 5% HF, 35% HNO_3 MAG: 3/4X
MACROSTRUCTURE OF INTERSTITIAL PANCAKE DYM-1 WITH 0.202 TO 0.212 % OXYGEN CONTENT

H-16824

Figure 17

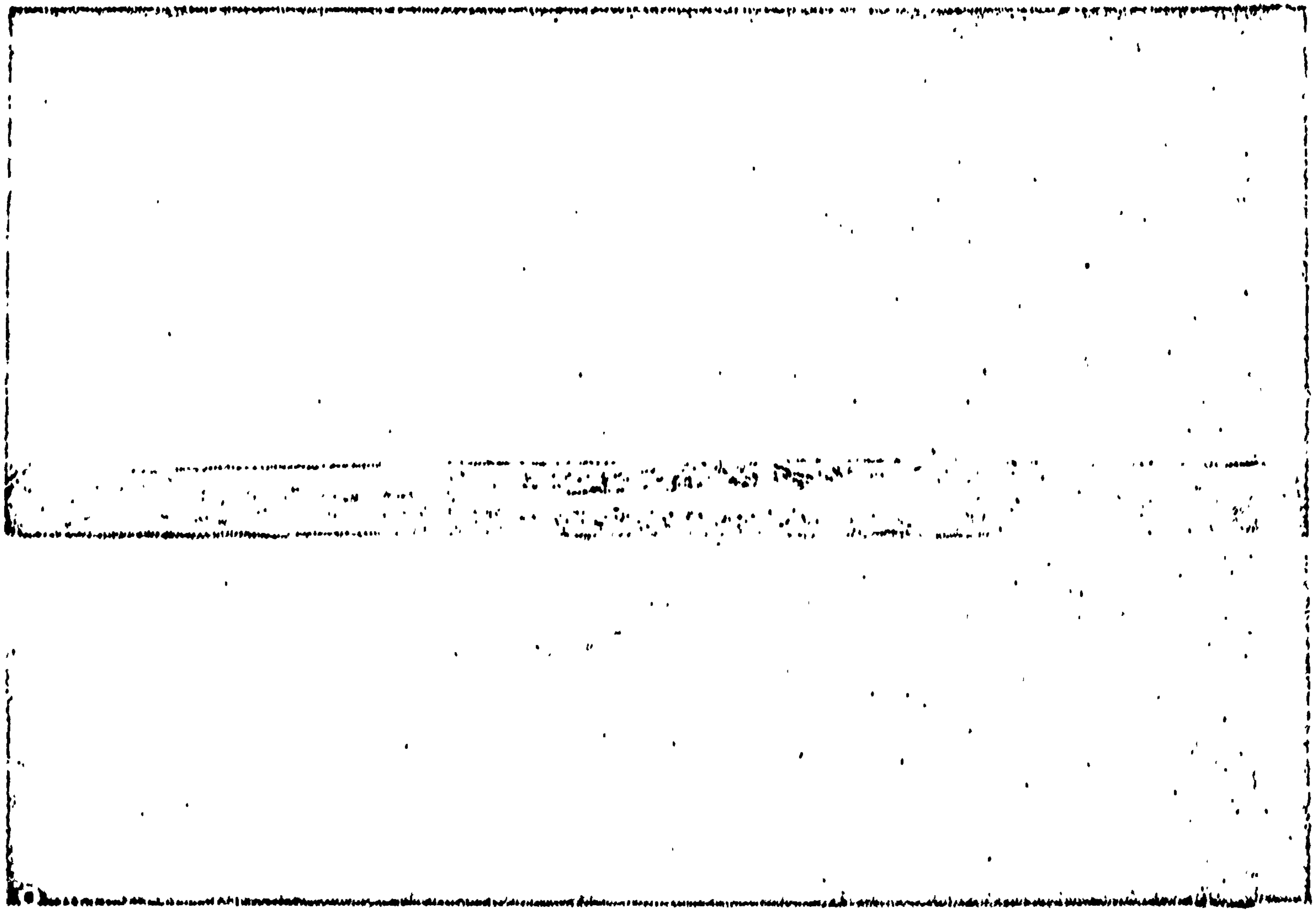


ETCHANT: 5% HF, 35% HNO3
MACROSTRUCTURE OF INTERSTITIAL PANCAKE DYN-1 WITH 0.158
TO 0.183% OXYGEN CONTENT

MAG: 3/4X

H-16825

Figure 18



ETCHANT: 5% HF, 35% HNO_3 MAG: 3/4X

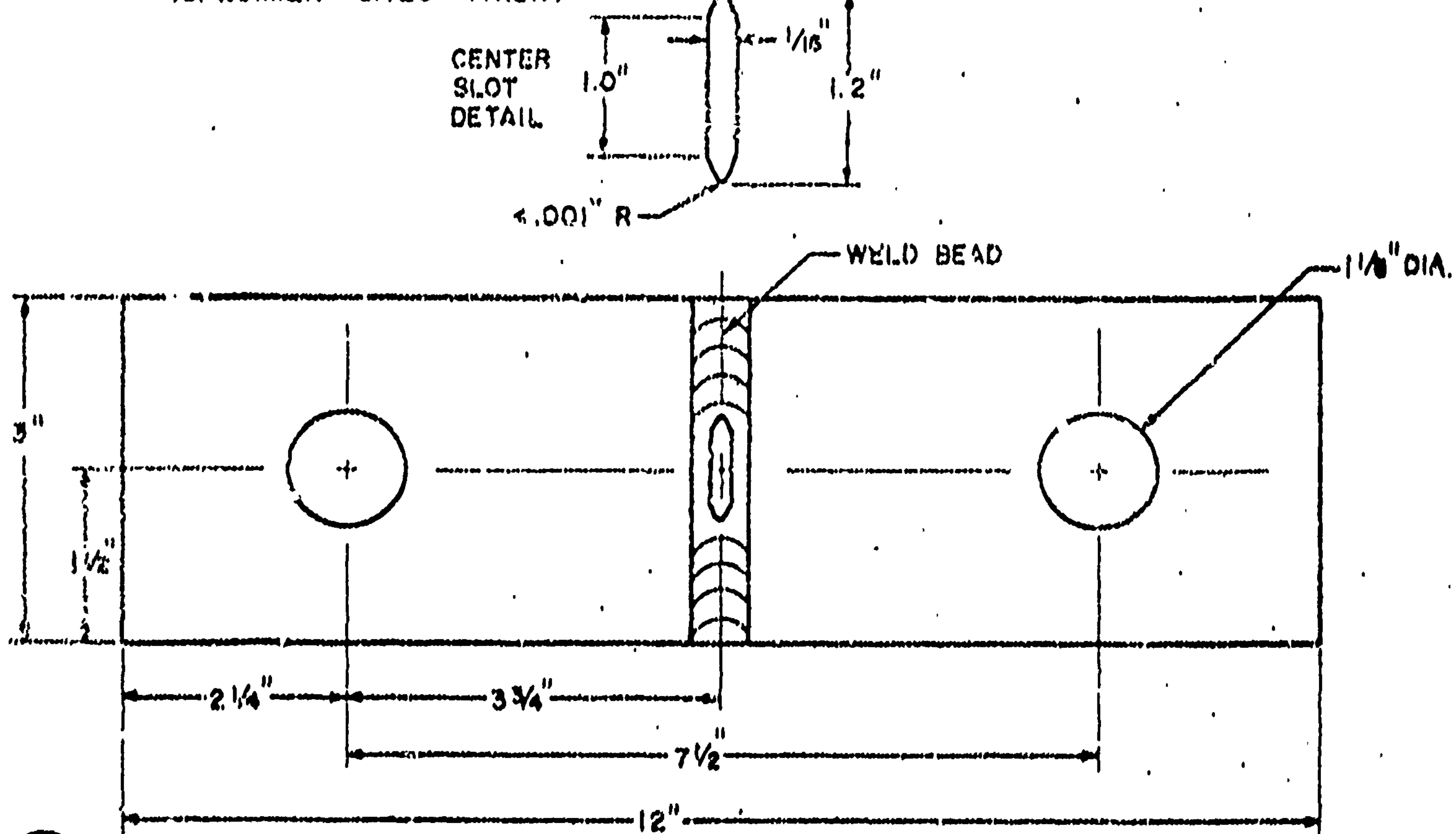
MACROSTRUCTURE OF INTERSTITIAL PANCAKE DYS-1 WITH 0.126 TO 0.202 % OXYGEN CONTENT

H-16828

Figure 19

ASTM STANDARD 3 x 12 INCH Gc SPECIMEN WITH NOTCHES AT WELD CENTER USED FOR TESTING TIG-WELDED MATERIAL (SPECIMENS WERE ALSO USED WITH NOTCHES IN HEAT-AFFECTED ZONE)

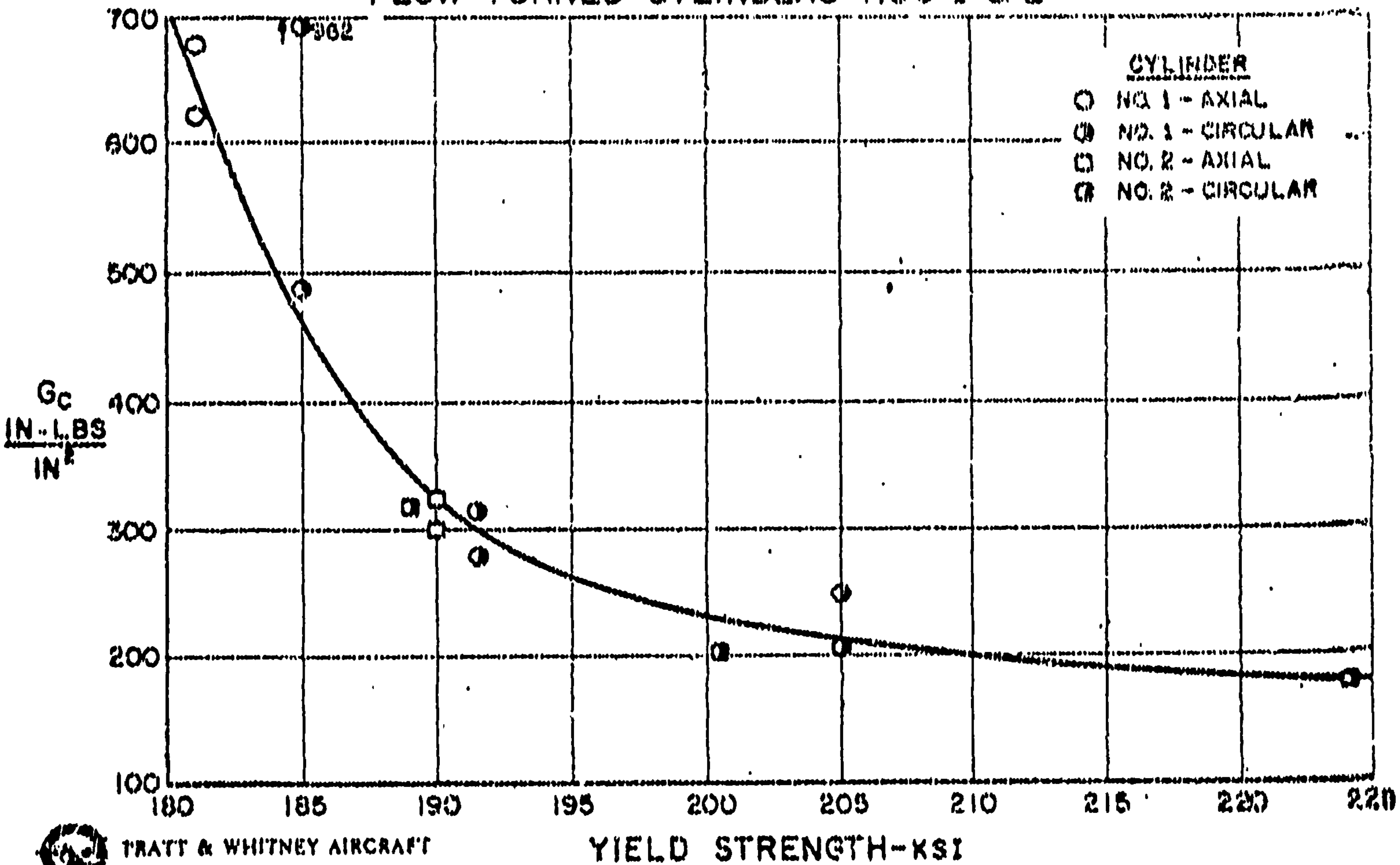
(SPECIMEN 0.125" THICK)



PRATT & WHITNEY AIRCRAFT
DIVISION OF
UNITED AIRCRAFT CORPORATION

Figure 20

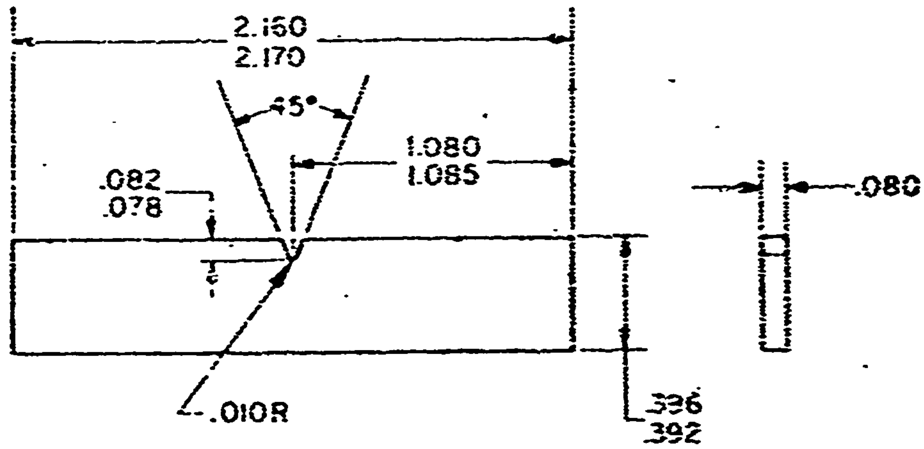
FRACTURE TOUGHNESS (G_C) & YIELD STRENGTH FOR B-120 VCA PERSHING FLOW-TURNED CYLINDERS NO's 1 & 2



PRATT & WHITNEY AIRCRAFT
DIVISION OF
UNITED AIRCRAFT CORPORATION

Figure 21

MODIFIED CHARPY IMPACT SPECIMEN USED FOR TESTING FLOW-TURNED CYLINDERS NO's 1 AND 2



PRATT & WHITNEY AIRCRAFT
DIVISION OF
UNITED AIRCRAFT CORPORATION

Figure 22

MODIFIED CHARPY IMPACT ENERGY ABSORPTIONS AND YIELD STRENGTHS FOR FLOW-TURNED CYLINDERS NO. 1 AND NO. 2 TESTED AT 70F AND -35F. SCATTER OF 70F RESULTS PREVENTED ANY CORRELATION.

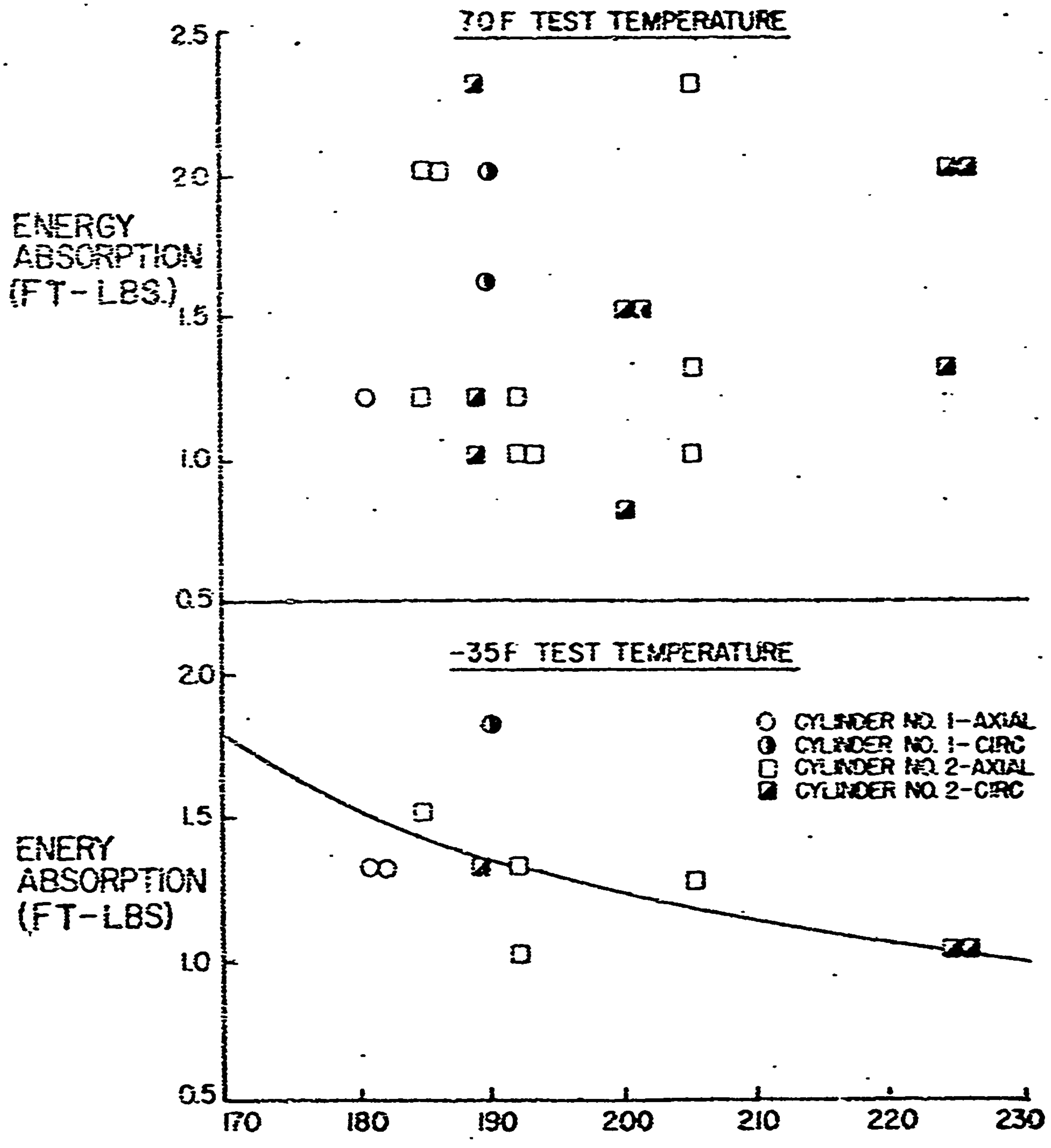


Figure 23

EXTERNALLY NOTCHED FRACTURE TOUGHNESS (G_c) SPECIMEN

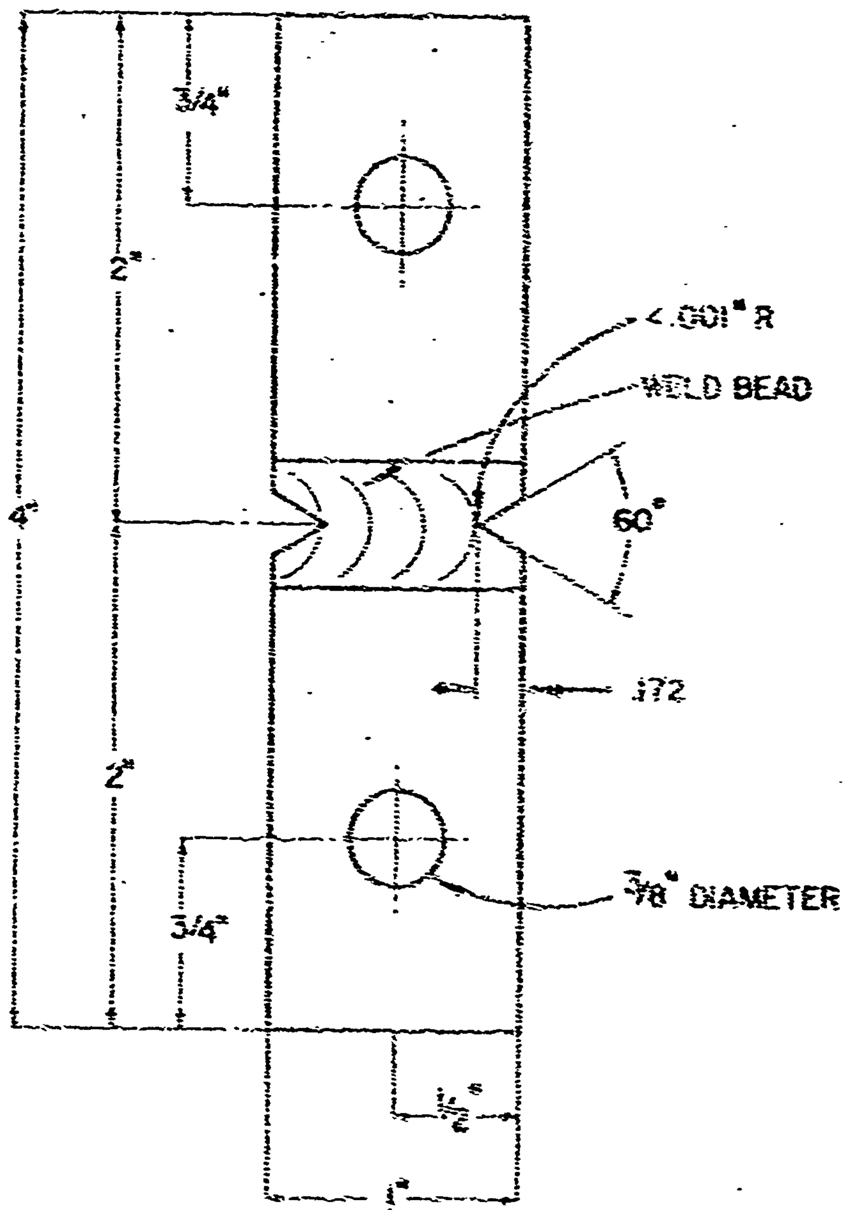
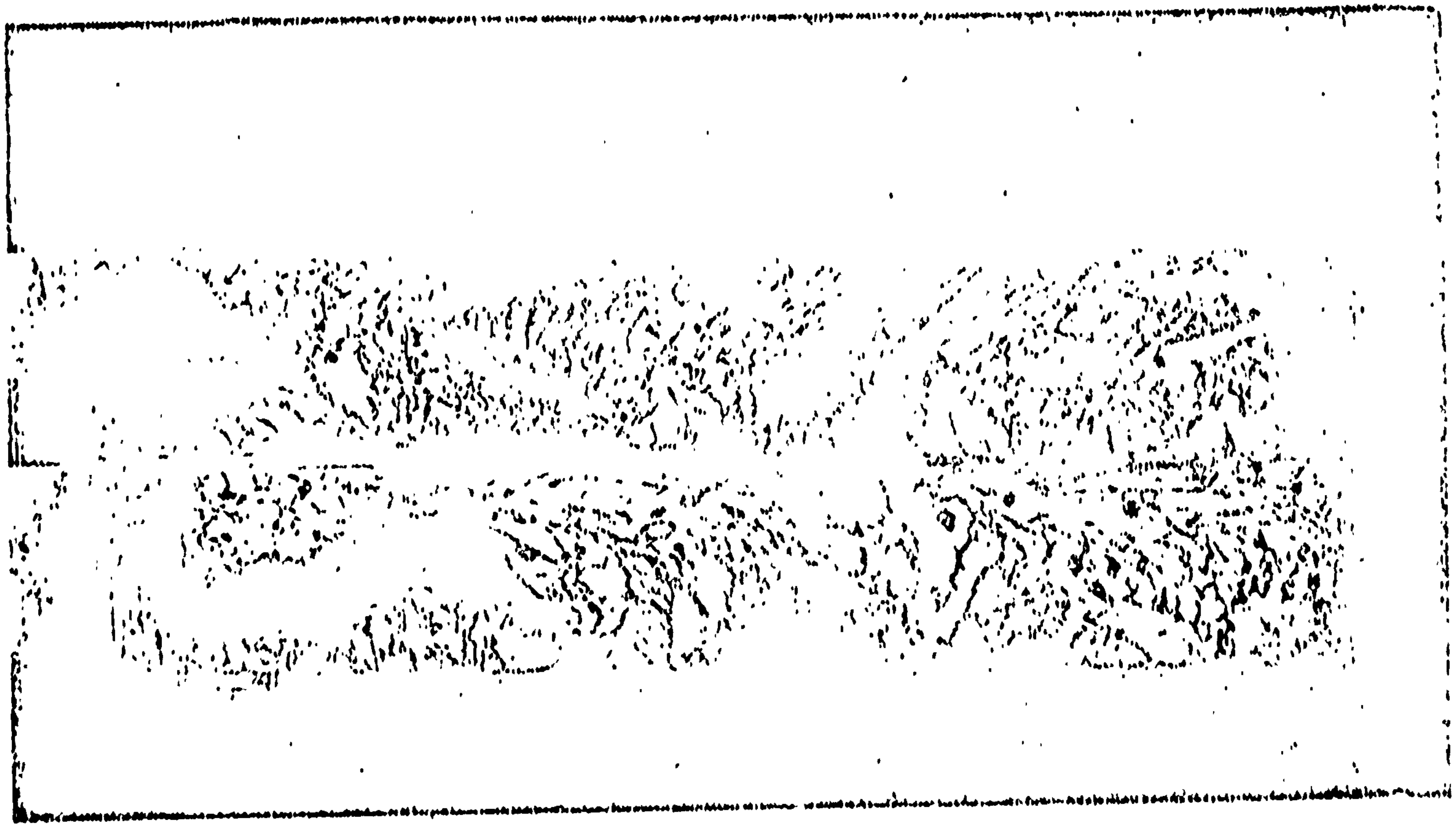


Figure 24

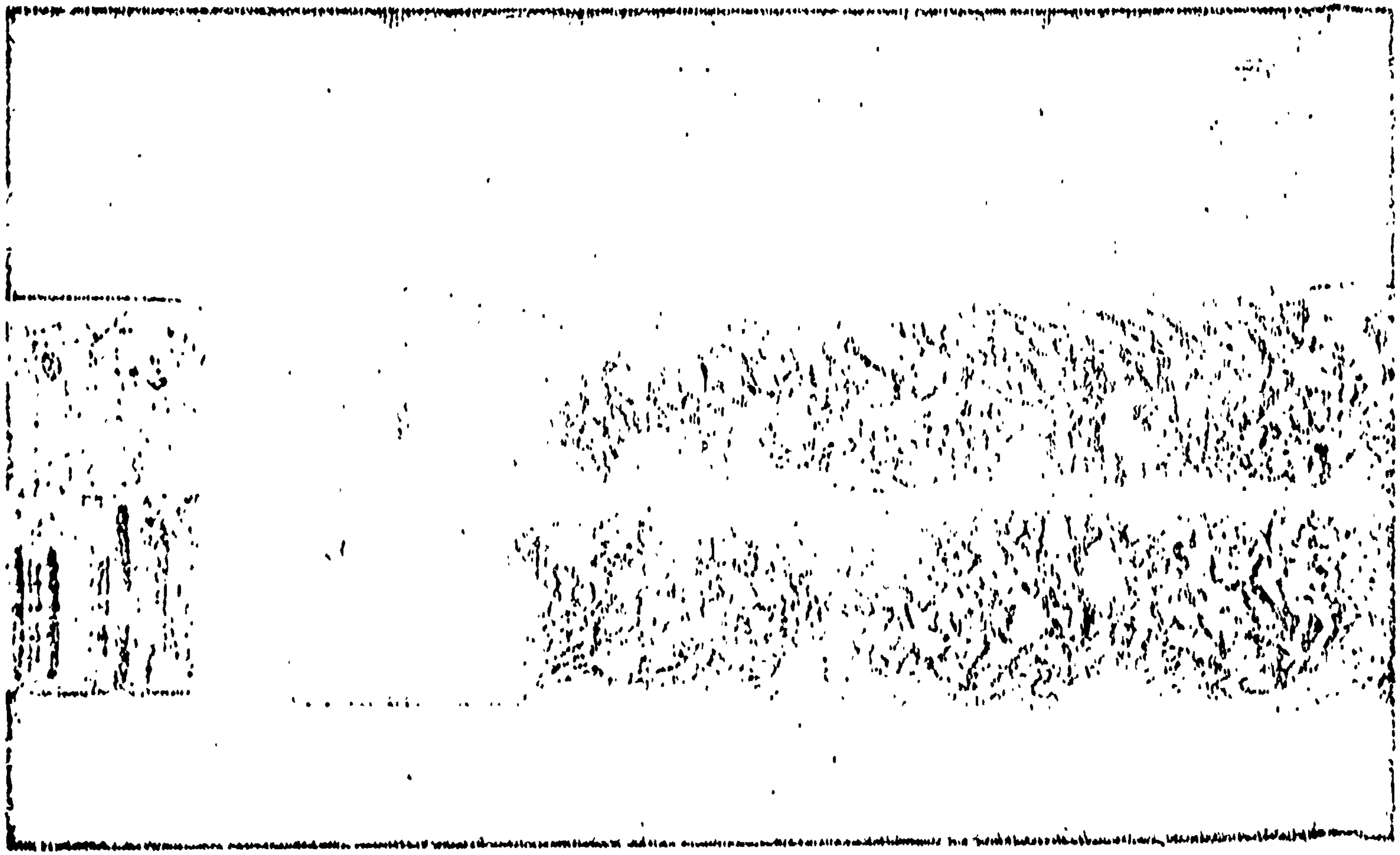


MAG: 11X

FRACTURE SURFACE OF TYPICAL FRACTURE TOUGHNESS SPECIMEN FROM B-120 VCA TIG WELD WHICH HAD G_c OF 164 IN-LBS/IN^2. BRACKETS INDICATE EXTENT OF SLOW CRACK PROPAGATION. NOTE COARSE-GRAINED CLEAVAGE FACETS AND PARTIALLY INTERGRANNULAR FAILURE.

H-16753

Figure 25

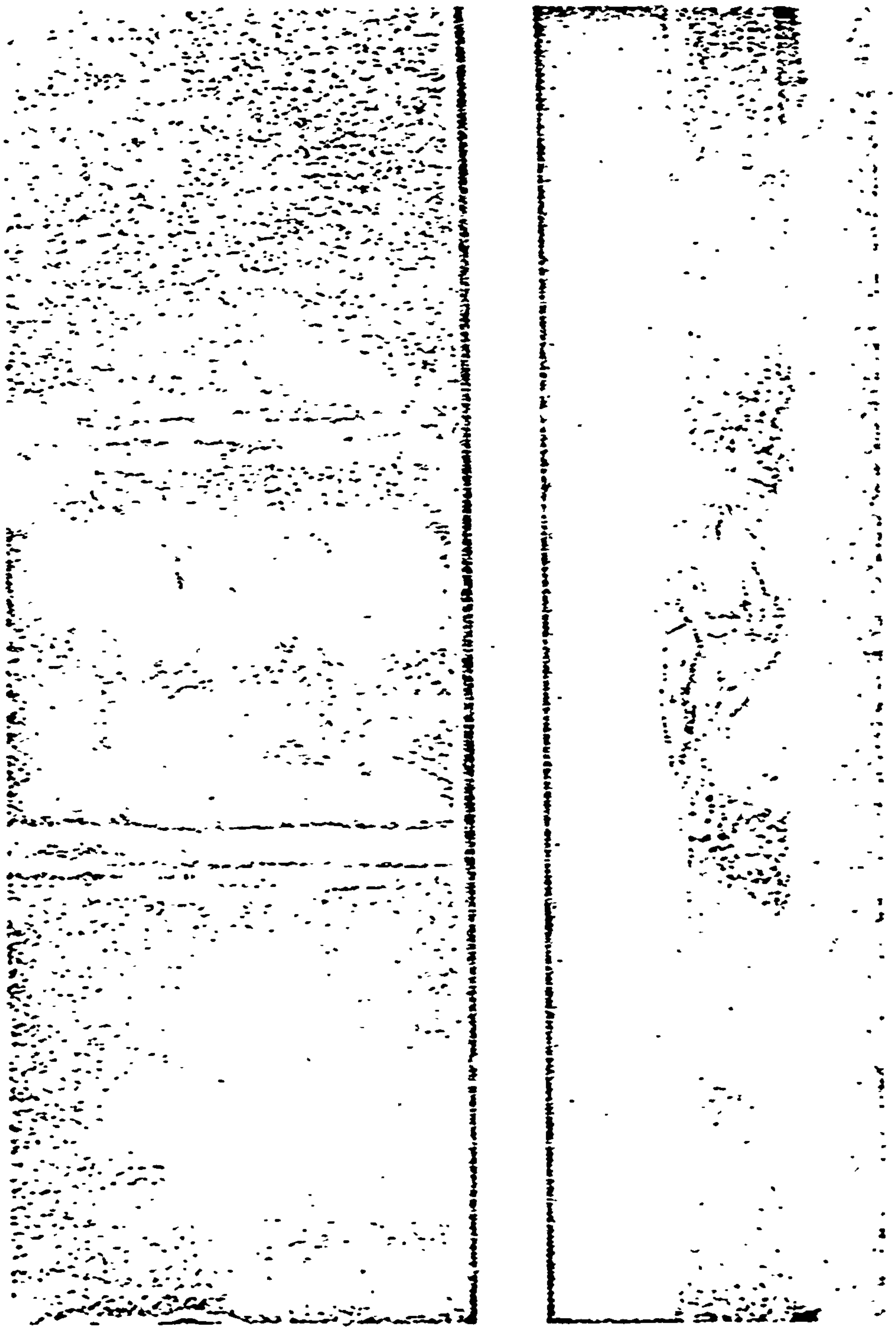


MAG: 11X

FRACTURE SURFACE OF FRACTURE TOUGHNESS SPECIMEN FROM 8-120 VCA TIG WELD WHICH HAD G_c OF 1180 IN-LBS/IN^2. BRACKETS INDICATE EXTENT OF SLOW CRACK PROPAGATION. NOTE FINER GRAIN SIZE.

H-16754

Figure 26



ETCHANT: 5% HF, 95% HNO3 MAG: 8X
MACROSTRUCTURE OF WELD FACE (TOP) AND TRANSVERSE SECTION (BOTTOM) OF B-120 VCA. TIG WELD

H-16749

Figure 27

INTERNALLY NOTCHED FRACTURE TOUGHNESS (G_c) SPECIMEN BEING CONSIDERED FOR TRANSVERSE WELD TOUGHNESS TESTING

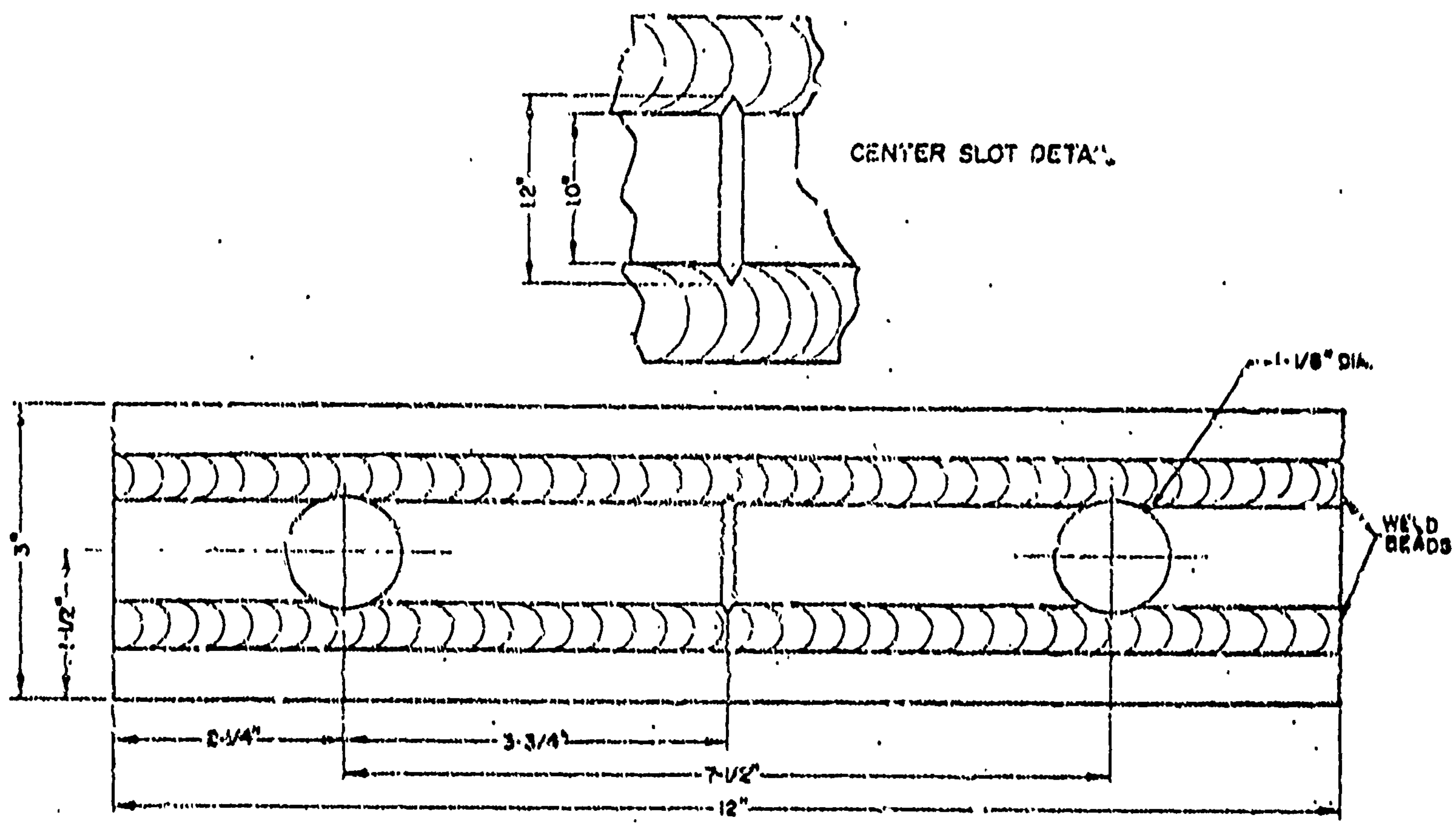
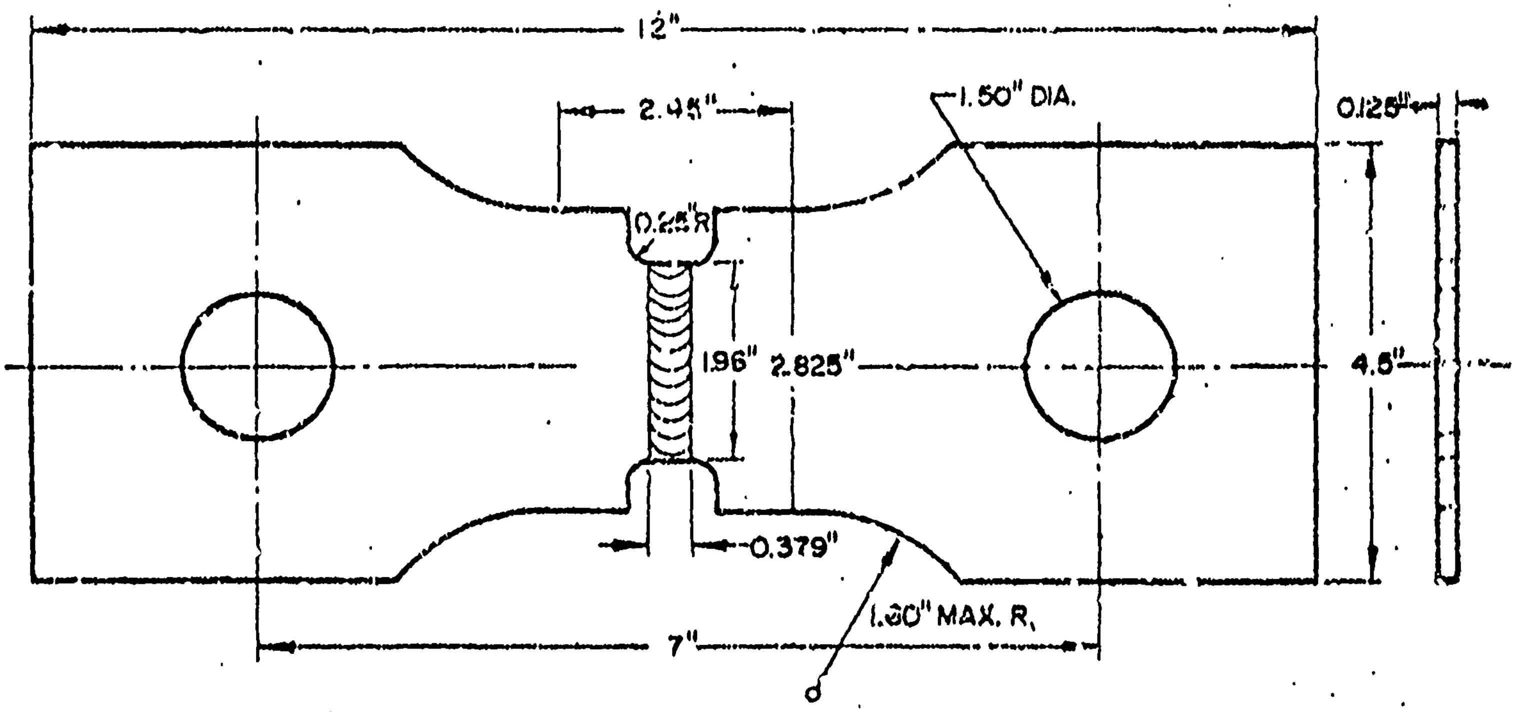


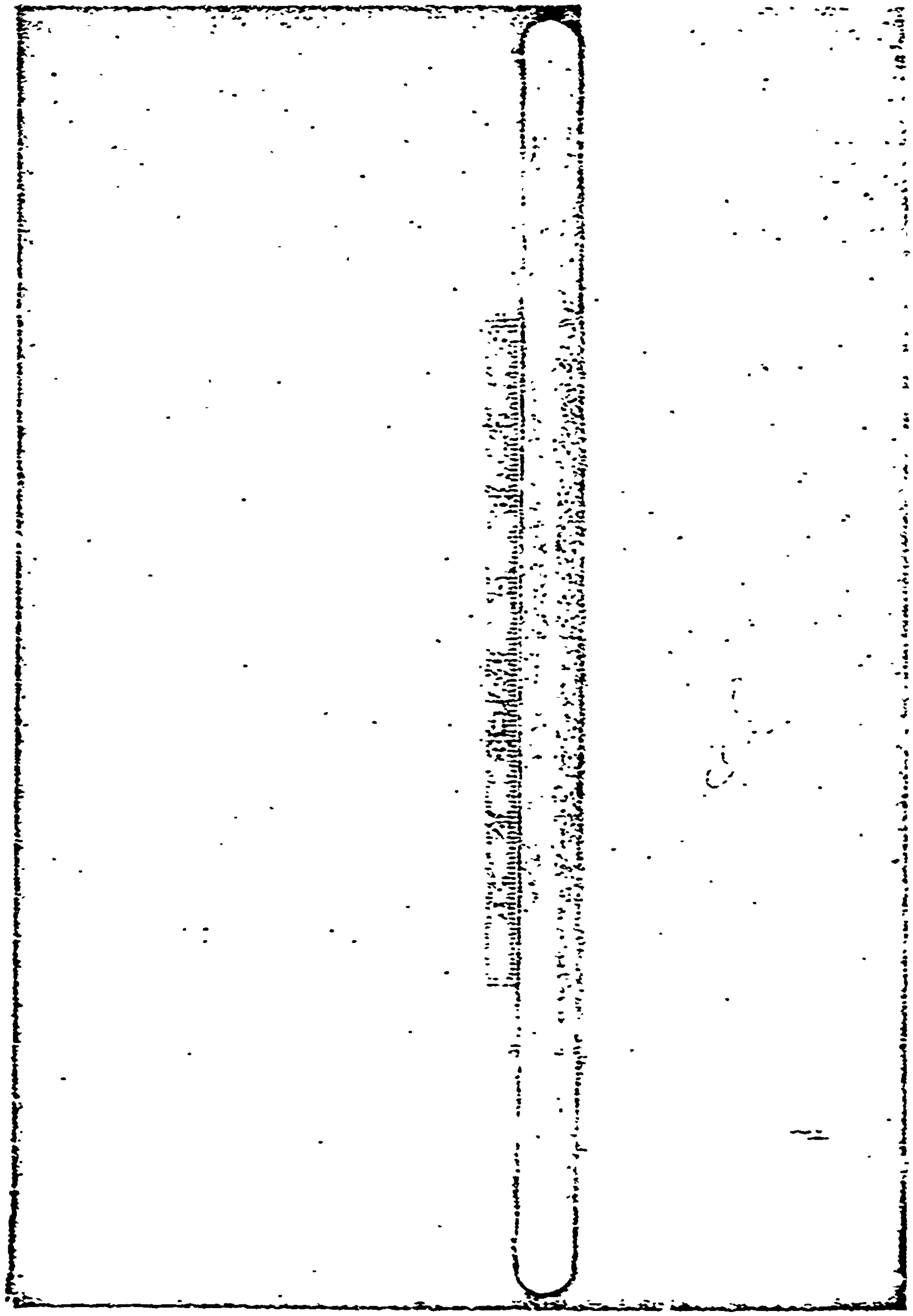
Figure 23

CURTISS-WRIGHT (BIAXIAL STRESS FIELD) SPECIMEN
USED FOR TESTING TIG-WELDED MATERIAL
(SPECIMEN 0.125" THICK)



PRATT & WHITNEY AIRCRAFT
DIVISION OF
UNITED AIRCRAFT CORPORATION

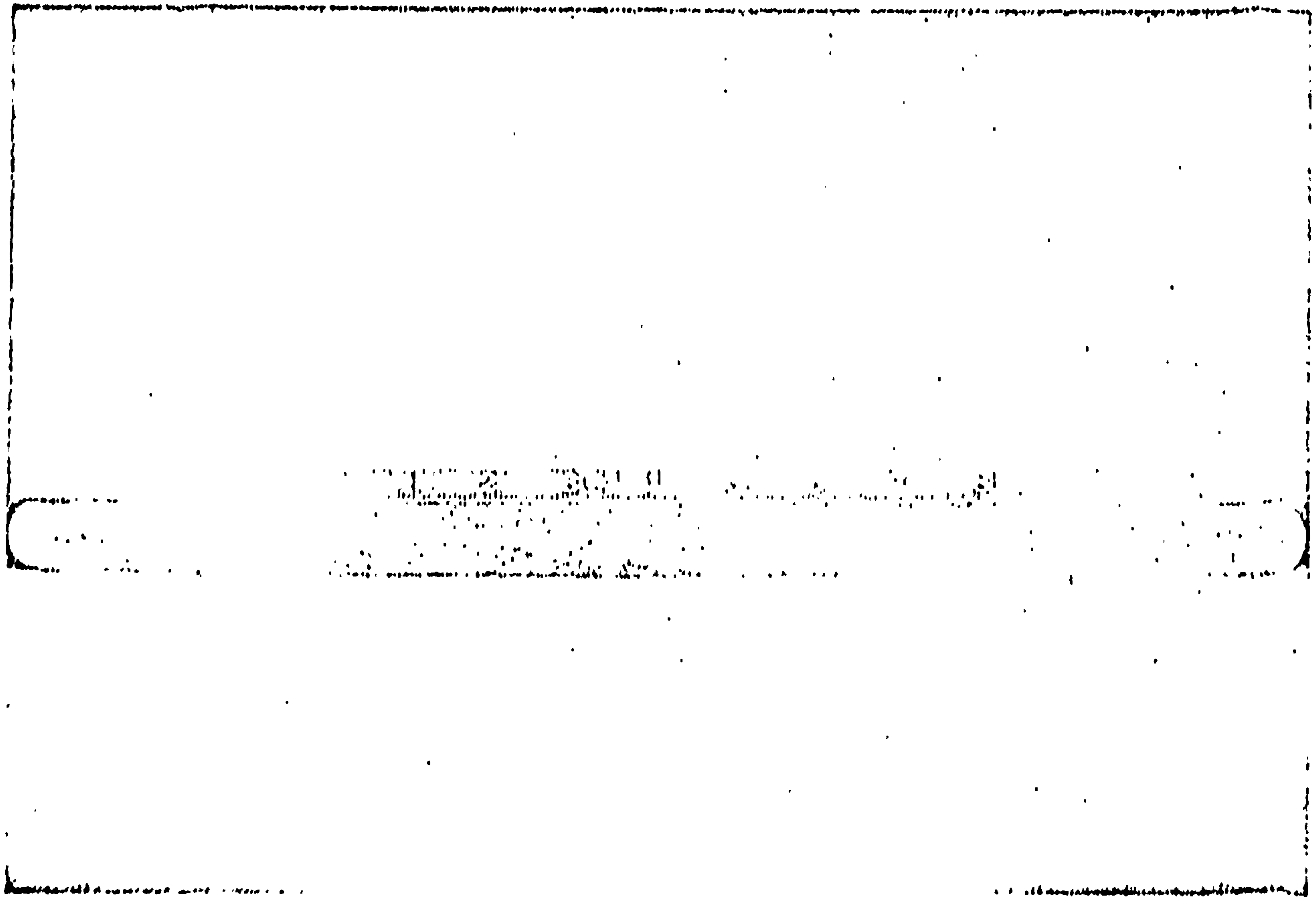
Figure 29



ETCHANT: 5% HF, 35% HNO3 MAG: 9/16X
MACROSTRUCTURE OF PANCAKE DYW-1 FORGED FROM 1700 F AT A
STRAIN RATE OF 7.32 INCHES/MINUTE.

H-16618

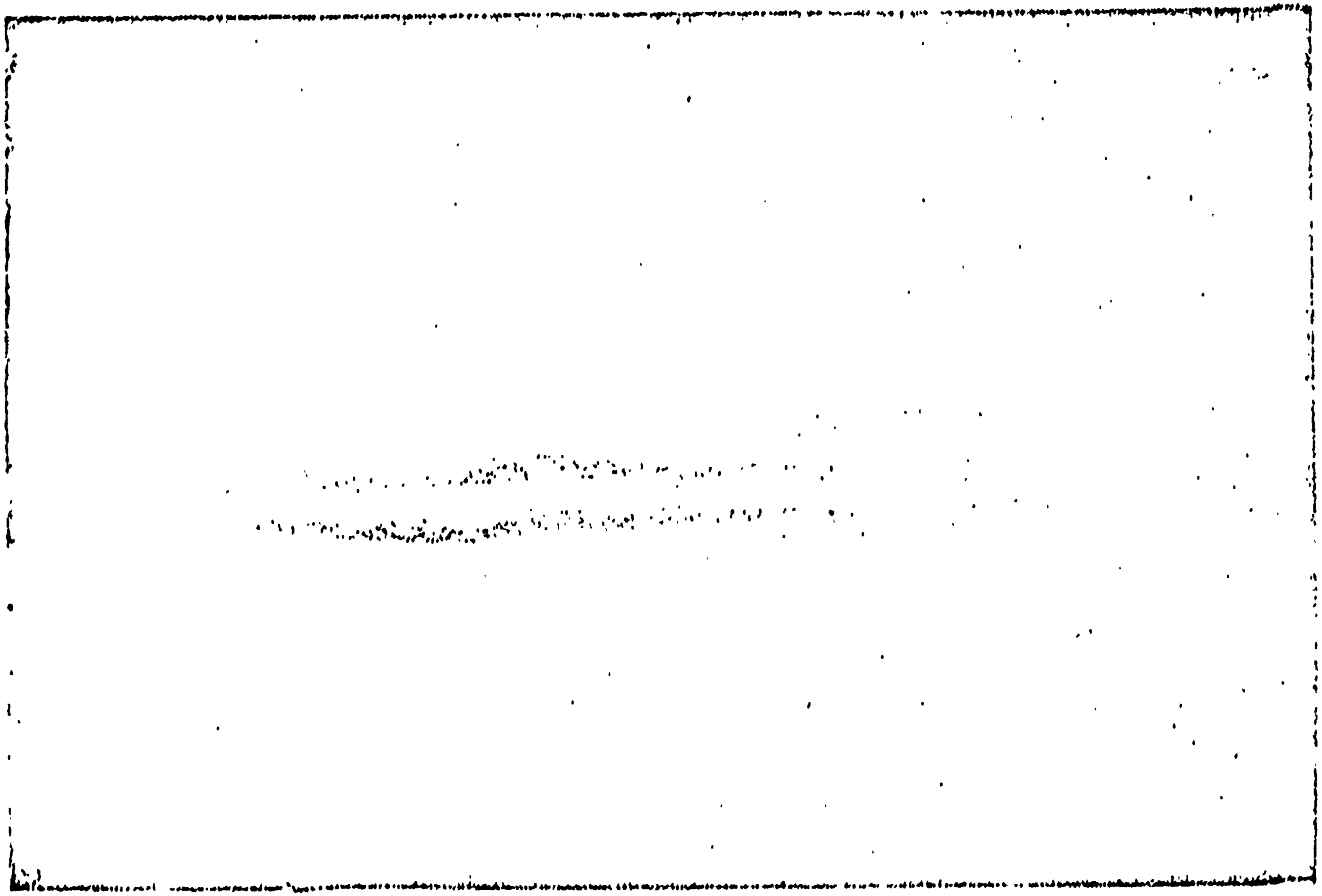
Figure 38



ETCHANT: 5% HF, 35% HNO3 MAG: 3/16X
MACROSTRUCTURE OF PANCAKE DYW-2 FORGED FROM 1700F AT A
STRAIN RATE OF 63.6 INCHES/MINUTE

H-16617

Figure 31



ETCHANT: 5% HF, 35% HNO_3 MAG. 9/16X
MACROSTRUCTURE OF PANCAKE DYW-3 FORGED FROM 1850F AT A STRAIN RATE OF 4.5 INCHES/MINUTE

H-16826

Figure 32

ETCHANT: 5% HF, 25% HNO3 MAG: 3/5X
MICROSTRUCTURE OF PANCAKE [illegible] FORGED FROM 1850F AT A
STRAIN RATE OF 20.3 INCHES/MINUTE

N-10827

Figure 33

APPENDIX C

Manufacturing Laboratories Report on
X-Ray Diffraction Analysis

MANUFACTURING LABORATORIES INC.

21 erie street • cambridge 39 • massachusetts

Technical Report

Preferred Orientation in Flow-Turned B-120VCA Titanium Alloy Sheet

by

S. V. Radcliffe and E. S. Meieran

Prepared for:

Materials Development Laboratory
Pratt and Whitney Aircraft
United Aircraft Corporation
East Hartford 8, Connecticut

December 1960

RESEARCH DIVISION

TABLE OF CONTENTS

Page No.

SUMMARY

Quantitative pole figures have been determined for B-120VCA titanium alloy sheet in the following conditions: annealed, cold-rolled (50% reduction) and aged, and flow-turned (50% reduction) and aged. It is shown that the deformation textures are $(100)[011]$ for the annealed sheet, $(100)[011]$ and $(111)[1\bar{1}0]$ for the cold-rolled sheet, $(100)[01\bar{1}]$ and $(111)[11\bar{2}]$ for the inner section of the flow-turned sheet, and $(111)[11\bar{2}]$ for the outer section of the flow-turned sheet. Reported variations in mechanical properties across the thickness and in the plane of flow-turned sheet can be understood in terms of the observed differences in preferred orientation.

I. INTRODUCTION AND OBJECTIVE

Studies of the cold-forming of B-120VCA titanium alloy into thin wall hollow cylinders by a flow-turning operation are currently in progress at Pratt and Whitney Aircraft. The alloy[1,2,3,5] has been developed recently for applications, such as rocket motor cases, where extremely high strength-to-density ratio is required. The composition of the alloy (13 wt.% vanadium, 11% wt. chromium and 4 wt. % aluminum) is such that all the alloying elements are taken into solution on heating into the beta phase region and that beta is retained as a metastable phase on air-cooling to room temperature. The metastable beta, which has a body-centered cubic structure, can be decomposed by aging at moderate temperatures. In the solution-treated condition, the alloy is soft and ductile, but aging brings about a substantial hardening. Cold-forming operations can be conducted readily on the solution-treated alloy without simultaneous decomposition of the beta phase[1].

The Pratt and Whitney studies have shown that, in contrast to annealed or cold-rolled and aged sheet, the flow-turned alloy exhibits variations in mechanical properties both in different directions in the plane of the material and across its thickness. The study of crystallographic orientation which is described herein was undertaken with the objective of determining whether these variations in mechanical properties could be related to the nature of the preferred orientation induced by flow-turning.

2. EXPERIMENTAL PROCEDURE

2.1 X-ray Method

Pole-figures for describing preferred orientation in polycrystalline metal sheet are usually determined by quantitative x-ray spectrometer techniques using a Geiger counter[6,7]. X-ray reflection methods for flat sheet specimens, such as that due to Schultz, provide data only for the central part of the pole figure, and the outer region must be determined by a transmission method. Alternatively, a reflection method alone can be used if specimens of special shape are cut from the sheet. Such methods have been described by Norton, Borie and Chernock and Wahl[8].

In the Norton method, a series of cylindrical specimens is cut so that the axis of each makes a different angle with the rolling direction. Each specimen provides data along one diameter of the pole figure. Borie uses a single laminated spherical specimen made up from sheet. The sphere is rotated simultaneously through the angle between the reference direction and the diffraction plane pole and through the azimuthal angle, producing data along a spiral path on the stereographic projection. The Buhler method employs a single laminated cubical specimen made up from sheet. Again the sample is driven so as to produce data along a spiral path on the stereographic projection. However, to provide complete coverage of the pole figure, separate runs must be made on each of three orthogonal cube faces.

Recently, the disadvantages of the inconvenient shape of the Borie type specimen and the multiple runs required in the Buhler method have been overcome in a method developed[9] for the rapid determination of deformation texture

in refractory metals. The method has been adopted here for the measurement of preferred orientation in B-120VCA titanium alloy.

The method uses a single laminated cubical specimen which is made up from the sheet under examination. The cube is sectioned so as to develop a diagonal face making equal angles with three orthogonal faces. Using the diagonal face as the reflecting surface, the specimen is set up in a Norelco motor-driven goniometer with conventional Schultz geometry so as to trace a spiral through the stereographic projection. The Norelco goniometer is modified to avoid the necessity of correcting the spiral for interaction between the two motor drives. The x-ray beam intensities for the chosen reflection are recorded continuously by means of a Geiger counter and strip-chart recorder. The rotations necessary to bring the cube diagonal face to the diffracting position are reversed on the stereographic projection by means of a Wulff net, with the result that the spiral track appears as a distorted spiral which covers the whole area of the appropriate quadrant of the pole figure. At discrete time intervals, the ratios of the reflected x-ray beam intensities to the random intensities of the same position of the specimen with respect to the beam, are read off the recorder chart. These ratios are plotted on the quadrant of the pole figure and boundaries drawn around areas of similar intensity ratio. Due to the specimen geometry, only a single run is necessary to determine the complete quadrant of the pole figure.

In practice, analysis of the pole figure is facilitated by plotting the data points for the various intensity ratios in different colors. Due to the difficulty of making a multi-colored reproduction, an example is not included in this

report. However, the black-and-white reproduction of a {110} pole figure shown in Figure 1 illustrates the detail of the intensity distribution which the method provides. The frequency of the data plotting is indicated by the partial spiral included in the figure.

2.2 Specimen Preparation

Samples of B-120VCA titanium alloy sheet in the following conditions were obtained in the form of 1 inch squares from the Materials Development Laboratory, Pratt and Whitney Aircraft:

(1) Mill annealed (1/8 in. thick)

(2) Cold rolled (50% reduction to 1/16 in. thick) and aged at 850°F for 30 minutes.

(3) Flow-turned (50% reduction to 1/16 in. thick) from a 40 in. diameter ring-forging and aged at 850°F for 30 minutes

The cold-rolled and flow-turned samples had been cleaned with an alumina blast to remove surface discoloration due to oxidation during the aging treatment. The mill-rolling, cold-rolling and flow-turning directions were indicated by scribed arrows on the samples. In addition, the outside surface of the cylinder from which the flow-turned sample was obtained was indicated by the scribed designation "OD". The flow-turning direction is defined as being parallel to the axis of the cylinder.

Specimens for the measurement of preferred orientation were prepared in the form of cubes of 1/3 in. side by laminating pieces of the appropriate sheet sample together. The laminations were stacked so that the deformation direction in the sheet was maintained in the composite specimen. Each cube was sectioned in the manner indicated above, and the resulting diagonal face polished metallographically and lightly etched.

For the annealed and the cold-rolled conditions, cubical specimens were made up from laminations of the entire sheet thickness. Before laminating, each sample piece was lightly ground to ensure that the upper and lower surfaces were parallel. Approximately 0.005 in. was ground from each surface in this process.

For the flow-turned condition, two cubical x-ray specimens were made up, one of laminations taken from the outer section of the as-received sheet and one of laminations from the inner section. The laminations, approximately 0.015 in. thick, were prepared by grinding away the unwanted portion of the sheet thickness after first lightly grinding (not more than 0.005 in. of material) both surfaces to make them parallel. The textures of these specimens represent the average textures in the outer quarter and the inner quarter of the total section thickness.

3. EXPERIMENTAL RESULTS

The intensity distribution of the reflections from $\{110\}$ planes was obtained by the method described, using filtered copper radiation. The data for the four conditions - annealed, cold-rolled, flow-turned outer surface and flow-turned inner surface - are presented in the form of $\{110\}$ pole figures in Figures 2, 3, 4 and 5 respectively. To facilitate the comparison of preferred orientations, the number of intensity ranges available from the experimental data has been reduced for these pole figures.

With the exception of the mill-annealed material, all the samples exhibit distinct textures. The mill-annealed material, Figure 2, shows a slight indication of a $(100)[011]$ texture, but is otherwise close to random. For the deformed material, the nearest ideal preferred orientations, that is, the crystallographic planes and directions which lie parallel to the deformation direction, are indicated on each of the pole figures. These textures are summarized in Table I:

TABLE I

Textures Observed In B-120VCA Titanium Alloy Sheet

Sheet Condition	Principal Texture Components	
Mill annealed	- essentially random texture -	
Cold rolled	$(100)[011]$ $(111)[\bar{1}10]$	
Flow turned		
(a) inner section	$(100)[011]$	$(111)[\bar{1}12]$
(b) outer section		$(111)[\bar{1}12]$

4. DISCUSSION

4.1 Comparison of Textures

The textures observed in the deformed titanium alloy are illustrated schematically in Figure 6. It is seen that the (111) [11$\bar{2}$] component which is found in both sections of the flow-turned sheet conforms on rotation through 90^{o} to the (111) [1$\bar{1}$0] component found in the cold-rolled sheet. The remaining component of the cold-rolled sheet texture, (100) [011], is a component of the texture of the flow-turned inner section. It does not appear in the texture of the flow-turned outer section which has only a single component.

The relationships between these textures suggest that, although the flow-turning operation results in elongation of the material in the axial direction of the cylinder without any change in internal diameter, the principal distortion of material is in the circumferential direction. In the outer section, which is subjected to the greatest distortion from the flow-turning tool, a singular texture is developed. This texture is equivalent to one of the components which would be expected to result if rolling were performed in the circumferential direction of the cylinder. The inner section is less affected by the circumferential action of the tool, but is forced to elongate in the axial direction of the cylinder. In this section, a mixture of the outer-section texture and the texture expected for rolling in the axial direction is observed. The conclusion that the flow-turned outer section is subjected to the greatest degree of cold-working is supported by consideration of the mechanics of the deformation process and by the fact that the outer section age hardens more rapidly than the inner-section. This latter

point is illustrated by the comparison shown in Figure 7 of the aging response of flow-turned material. In addition, the figure indicates the greater over-all aging response of flow-turned material.

Although no data has been reported for the texture of flow-turned materials, the texture observed here for cold-rolled B-120VCA titanium alloy can be compared with that reported for other body-centered cubic metals and for a beta-titanium alloy. The characteristic rolling texture for body-centered cubic metals is considered[6] to be that shown by iron, namely, {100}[011], {111}[11$\bar{2}$] and {112}[1$\bar{1}$0]. Table I shows that of these components, only the {100}[011] is exhibited by the B-120VCA alloy. Recently, Albert, Liu and Cadoff[4] reported the rolling texture for a stable beta phase titanium alloy as {100}[100] and {112}[100]. It is likely that the latter component is a misprint for {112}[1$\bar{1}$0], since there is no [100] type direction in a {112} type plane. Even so, the texture is very different both from that found in iron and that observed here for B-120VCA alloy. In the absence of details of the composition and methods used in the work of Albert et al., it is impossible to resolve these differences.

4.3 Relationship Between Texture and Mechanical Properties

The textures of the cold-rolled sheet and the flow-turned inner section (illustrated in Figures 3, 5 and 6) are such that, on the basis of texture alone, the transverse properties of the rolled material would be expected to resemble the axial (longitudinal) properties of the flow-turned cylinder. Similarly, the longitudinal properties of the sheet should resemble the circumferential properties of the flow-turned inner-section. In practice, as shown in Figure 7, the yield strengths for these two deformation conditions are approximately the

same and are independent of direction of testing.

In the case of the outer section of the flow-turned material only the {111}[11$\bar{2}$] component is found, and the {100}[011] component is absent. The latter is usually dominant in body-centered cubic rolling textures. Thus, anisotropy in mechanical properties which might be characteristic of the {111}[11$\bar{2}$] texture should be observed in the outer-section. In the inner-section and the cold-rolled sheet where this component is a secondary one, no effects from anisotropy are apparent. As is shown in Figure 7, the outer-section does exhibit much stronger properties in the circumferential compared with the axial direction. The effect is so strong that it is still apparent, though to a lesser extent, in tests made on the entire sheet thickness. The very low value noted for the axial yield strength in the outer section is considered to be spurious. Only a single test was made, whereas all other tests were made in duplicate. Further tests of this condition are being made at Pratt and Whitney Aircraft.

5. CONCLUSIONS AND RECOMMENDATIONS

1. The texture of the wall of a flow-turned cylinder of B-120VCA titanium alloy differs accross the wall thickness and differs from that of cold-rolled sheet of the same alloy.

2. The texture of the inside section of the wall is $\{100\}[011]$, $\{111\}[11\bar{2}]$ and that of the outside section is $(111)[11\bar{2}]$.

3. The texture of the cold-rolled sheet is $\{100\}[011]$, $\{111\}[1\bar{1}0]$.

4. The differences between the mechanical properties of the cold-rolled sheet and the flow-turned material can be explained in terms of the differences in preferred orientation.

5. It is recommended that a study be made of the nature of the deformation involved in flow-turning and also of the relationships between the deformation and the resulting texture. In this way, it may be possible to change the processing variables, or modify the process itself, so as to control the deformation texture and produce desired mechanical properties.

5. REFERENCES

1. V. C. Petersen, H. B. Bomberger and M. B. Vardahl. "An Age-Hardening Titanium Alloy", Metals Progress (1959), Dec. 119.

2. R. A. Rawe, J. M. Dupouy and M. B. Bever, "Transformation Characteristics of a Beta-Phase Titanium Alloy", Trans. AIME, 218, (1960) 821.

3. L. E. Tanner, "Isothermal Transformation of Ti-13V-11Cr-3Al", ASM (1960), Preprint No. 206.

4. P. A. Albert, Y. C. Liu and L. Gatoff, "Deformation Textures of Titanium Alloys", AIME Philadelphia Meeting, October 1960, Research Abstract.

5. "Properties of Ti-13V-11Cr-3Al", Titanium Engineering Bulletin No. 9, published by The Titanium Metals Corporation of America, New York (1960).

6. C. S. Barrett "Structure of Metals", 2nd Edition (1952), McGraw-Hill, New York.

7. A. H. Geisler "Crystal Orientation and Pole Figure Determination" in ASM Seminar "Modern Research Techniques in Physical Metallurgy (1953).

8. W. P. Chernock and P. Wahl, "Preferred Orientation Specimen Holder for Use with the Norelco Diffractometer", Norelco Reporter (1955).

9. E. S. Meieran; to be published.

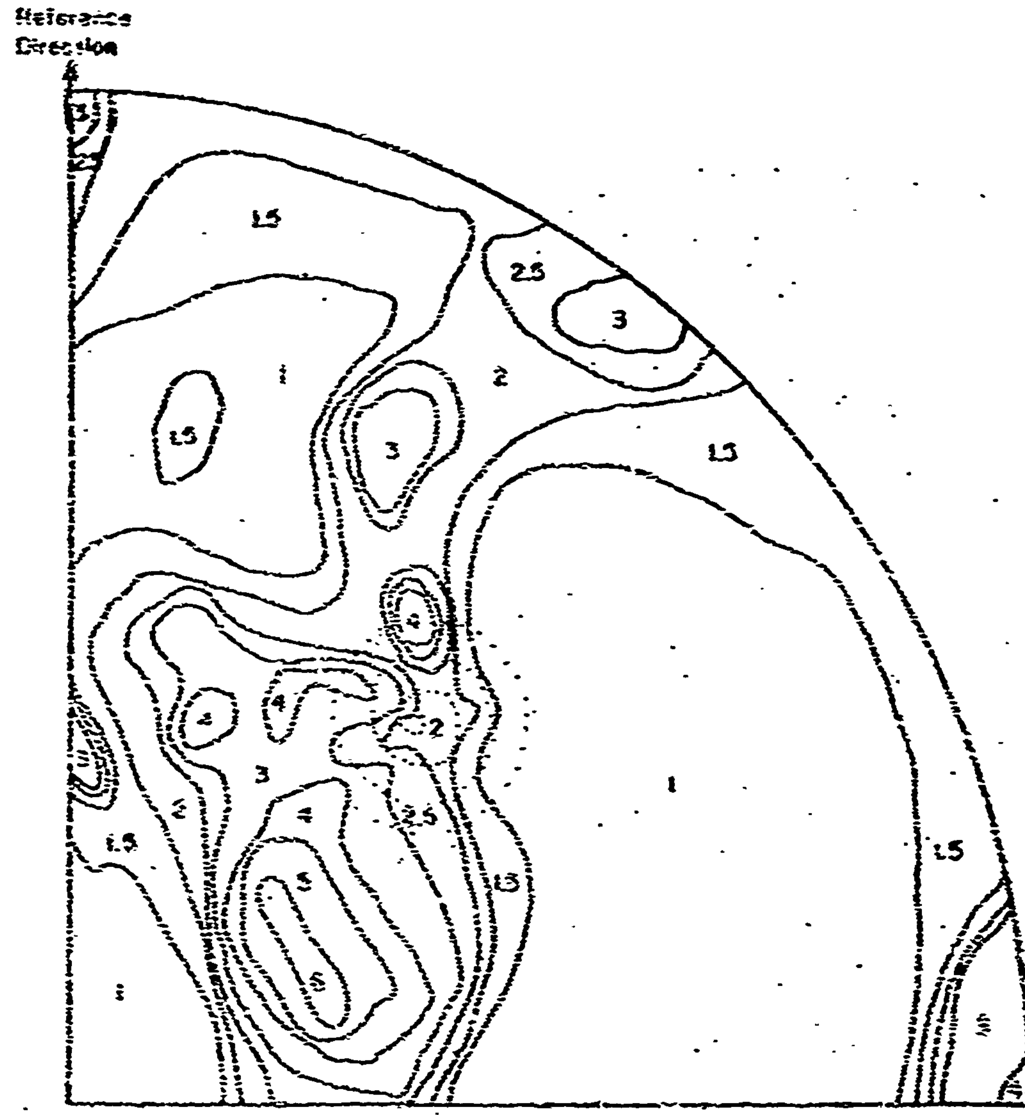


Fig. 1 Example of detailed intensity distribution of {110} poles obtained from tracing a spiral path on the stereographic projection. The numbers denote relative intensities. Only part of the spiral is shown. The data are for the inner surface of a flow-turned cylinder of B-120 VCA titanium alloy.

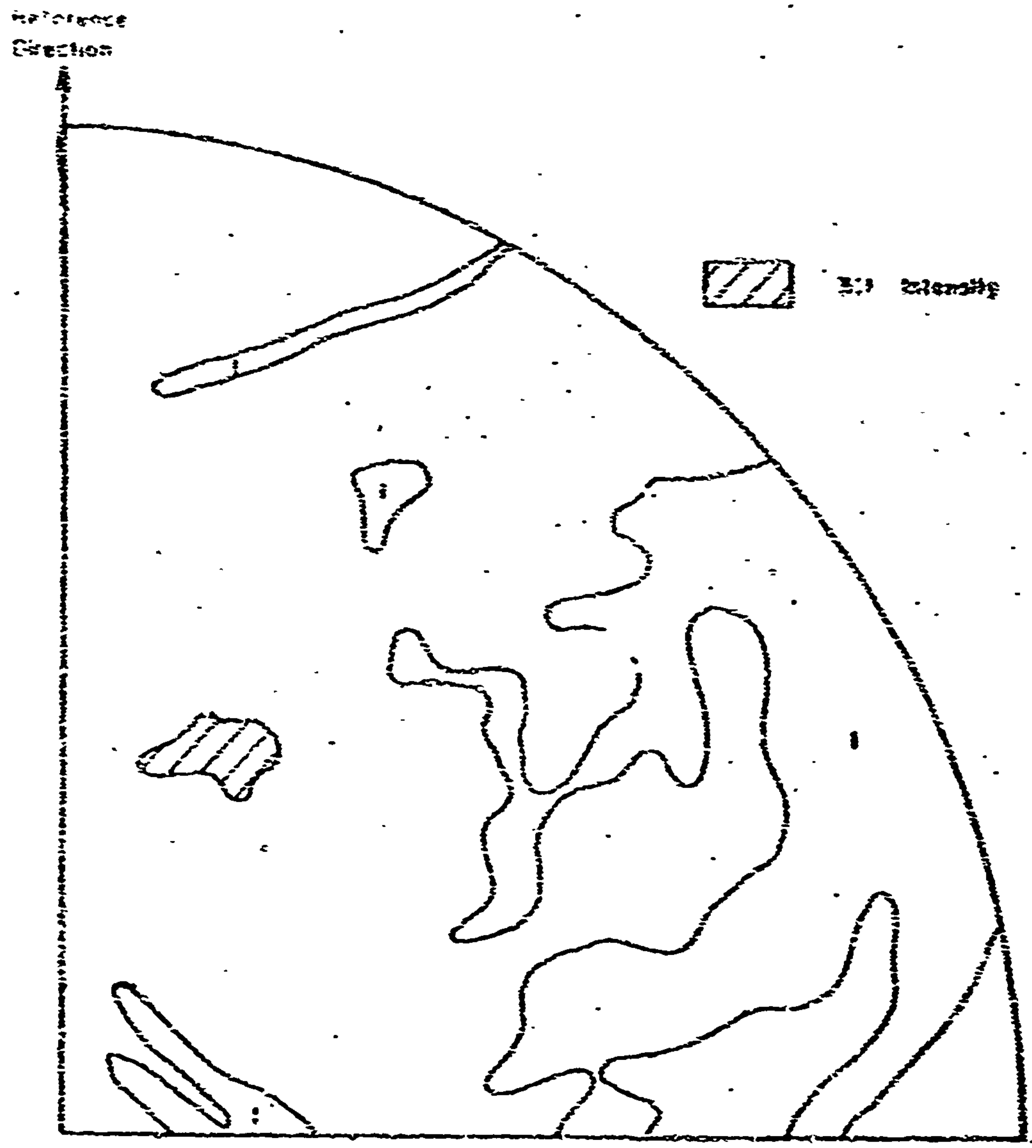


Fig. 2 {110} pole figure of B-120 VCA titanium alloy sheet, mill annealed.

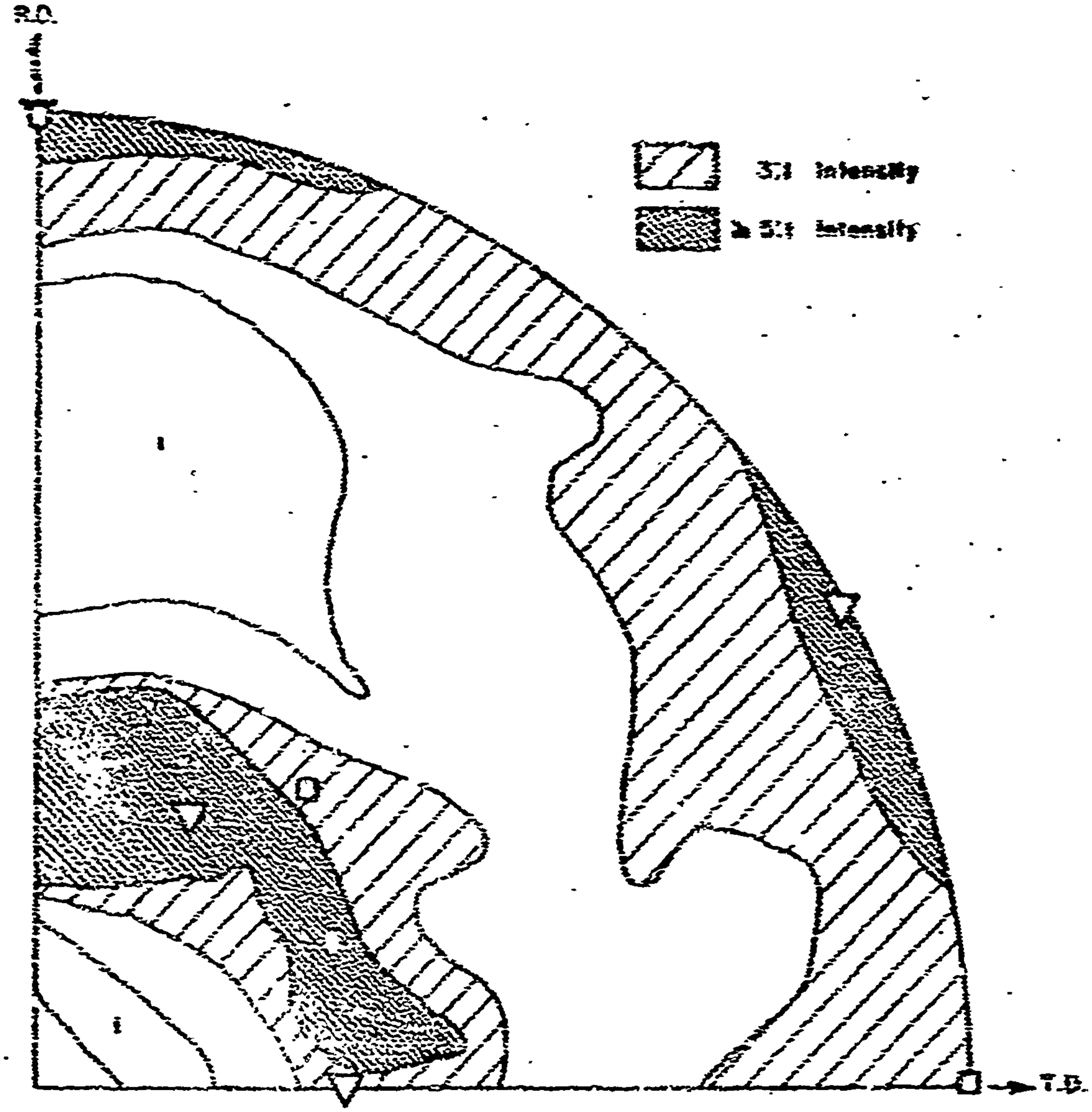


Fig. 3 {110} pole figure of B-120 VCA titanium alloy, cold-reduced 50% by rolling and aged at 850°F for 30 minutes. Nearest ideal orientations are indicated as follows: □ (100) [011], ∇ (111) [1̄10].

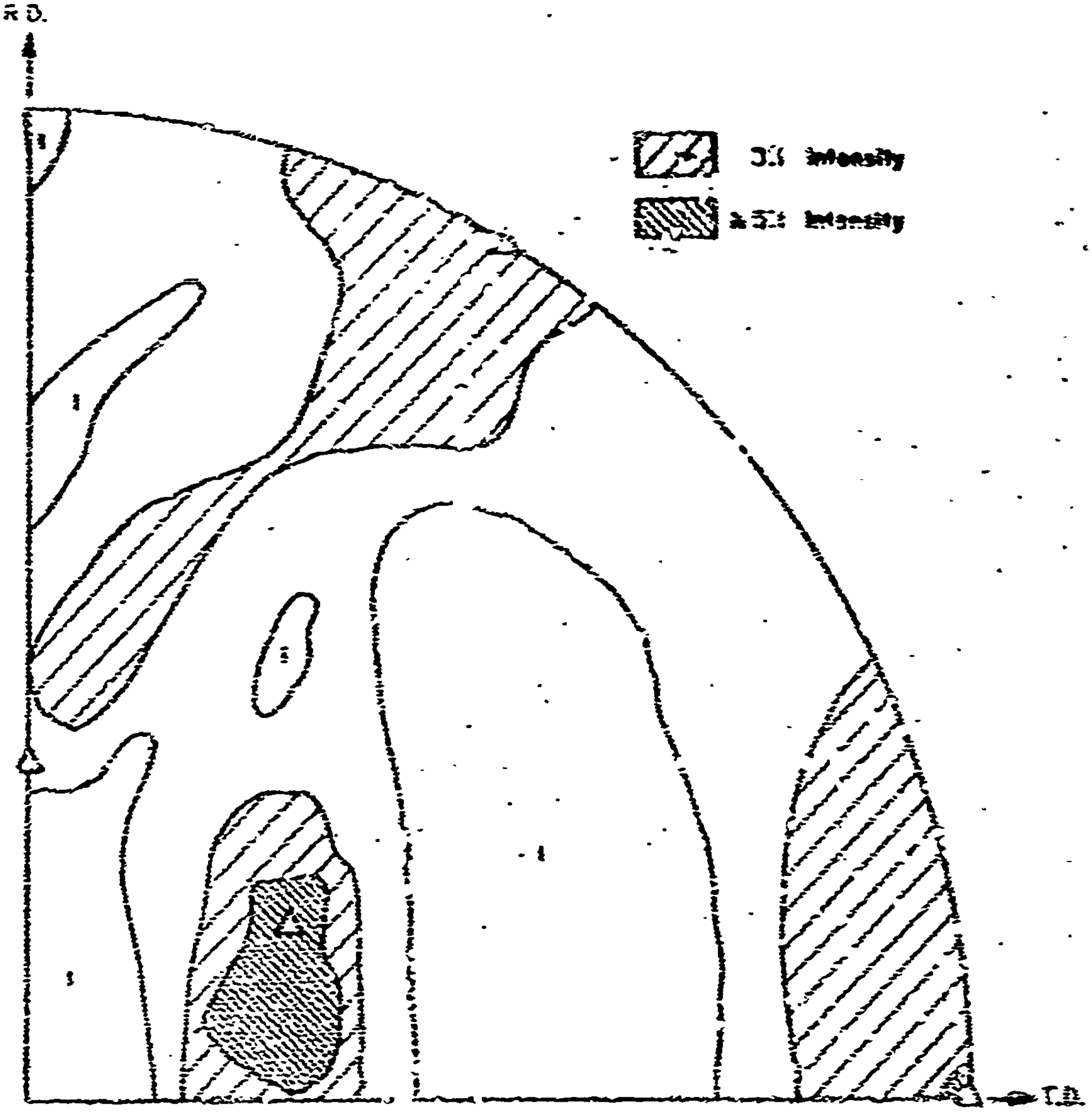


Fig. 4 {110} pole figure of B-120 VCA titanium alloy cold-reduced 50% by flow-turning and aged at 850°F for 30 minutes. Specimen material taken from the outside portion of the wall of the flow-turned cylinder. Nearest ideal orientation is indicated as : Δ (111) [11$\bar{2}$].

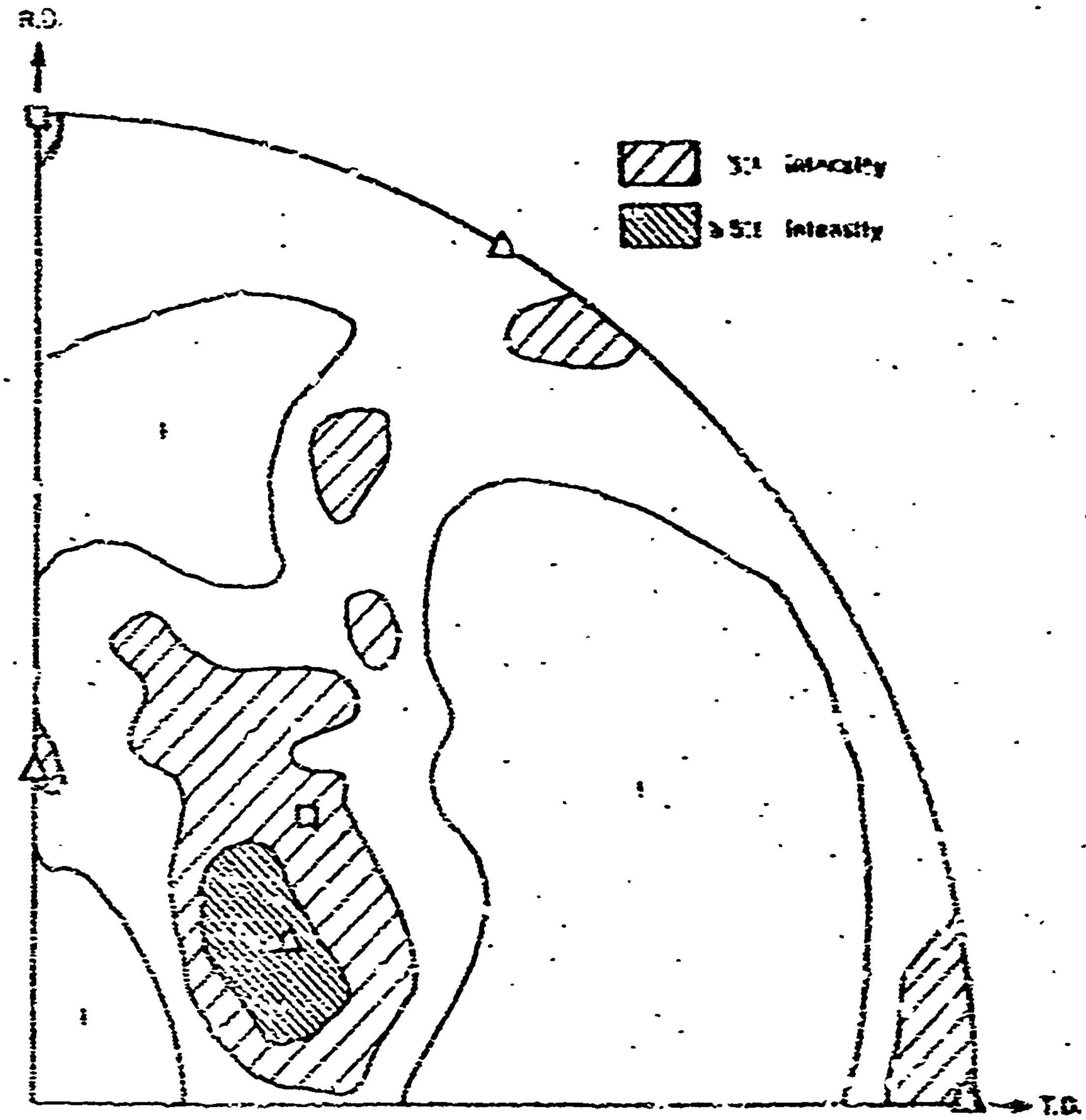


Fig. 5 {110} pole figure of B-120 VCA titanium alloy, cold-reduced 50% by flow-turning and aged at 950°F for 30 minutes. Specimen material taken from the inside portion of the wall of the flow-turned cylinder. Nearest ideal orientations are indicated as follows □ (100) [011] , △ (111) [112] .

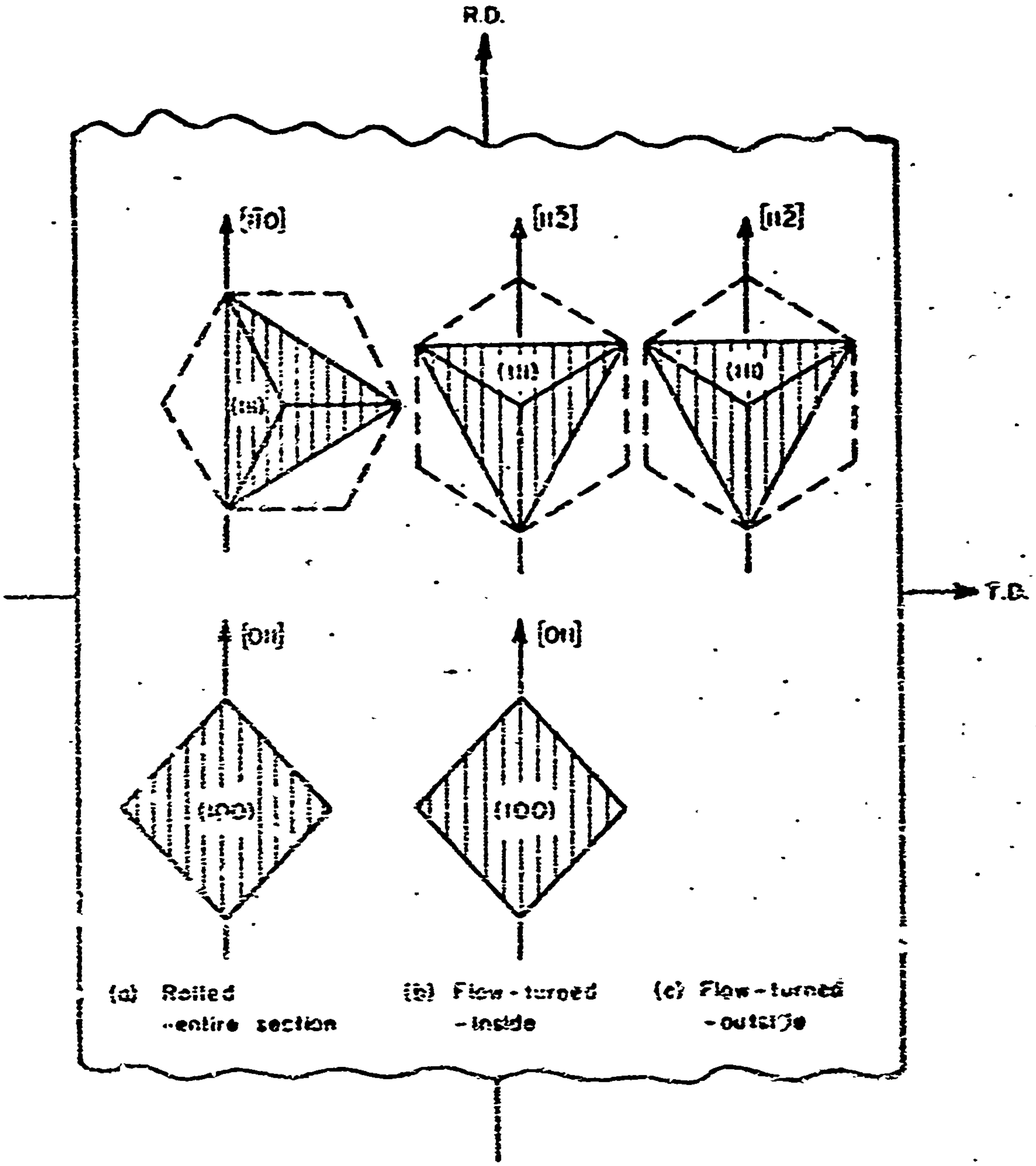


Fig. 6 Model illustrating the nearest ideal orientations observed in cold-reduced, B-120 VCA titanium alloy. The surface of the cold-reduced sheet is in the plane of the paper.

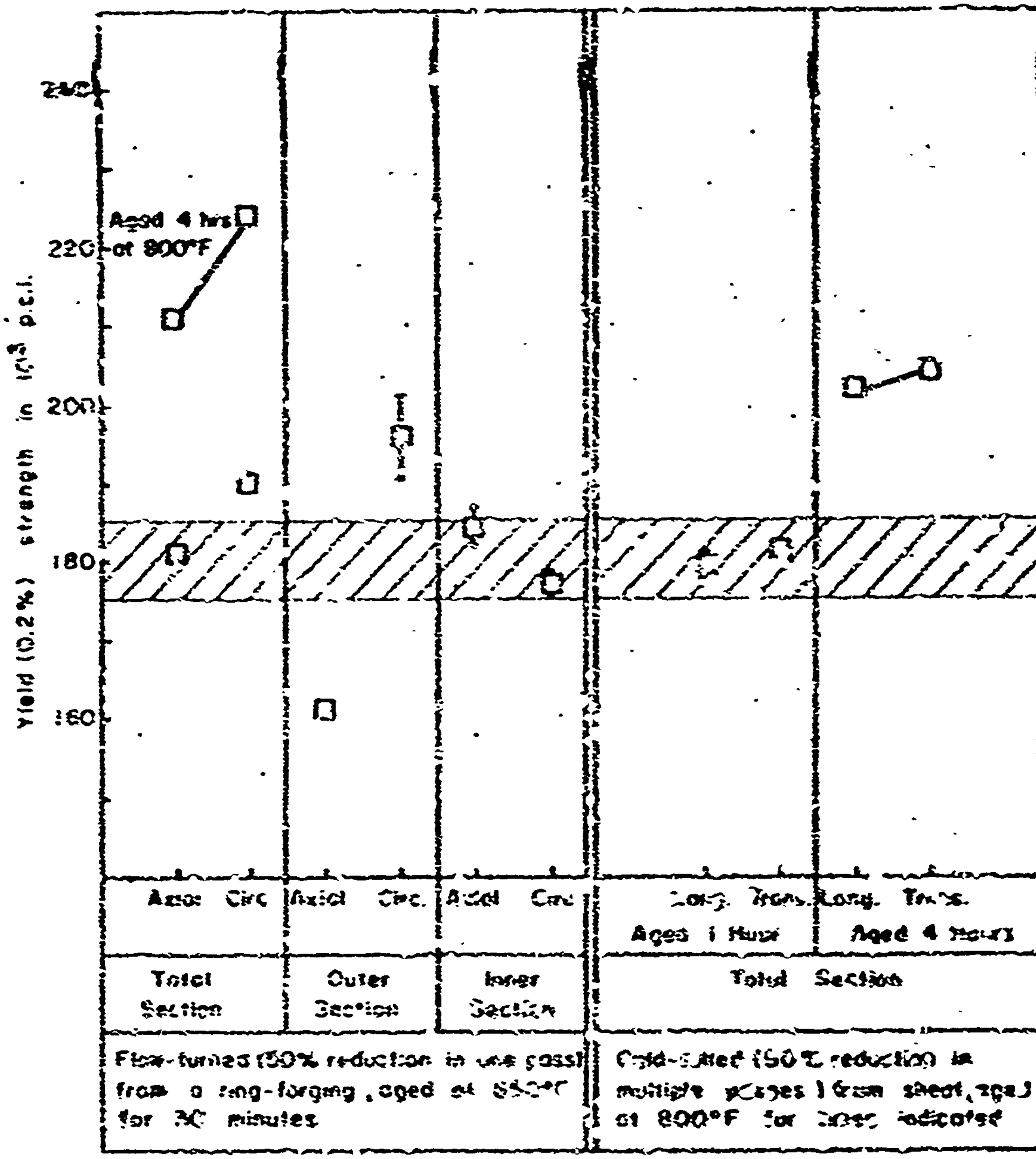


Fig. 7 Directional yield strength of B-120 VCA titanium alloy after 50% cold-reduction by rolling and by flow-turning (Tensile data obtained from Materials Development Laboratory, Pratt and Whitney)

Best Available Copy

Pratt & Whitney Aircraft Division of United Aircraft Corporation, East Hartford 8, Connecticut.
SECOND QUARTERLY REPORT ON RESEARCH AND DEVELOPMENT OF TITANIUM ROCKET MOTOR CASES, by R. P. Brody and F. A. Crosby, January 31, 1961. 101 p. incl. illus. (Project No. TB4-004) Contract No. DA-19-020-ORD-5230

Unclassified Report

The results of work performed during the quarter from October 1 through December 31, 1960 on the development of a high strength, lightweight, titanium alloy rocket case, are reported. These results include 1) tensile tests, chemical analysis, and microexamination of a press-forged pancake forging, 2) tech-
(over)

UNCLASSIFIED

1. Rockets, Motor Cases
2. Titanium Fabrication
3. Titanium Alloys

I. Brody, R. P. and Crosby, F. A.
II. U. S. Army Ordnance Corps, Watertown Arsenal
III. Contract DA-19-020-ORD-5230

Pratt & Whitney Aircraft Division of United Aircraft Corporation, East Hartford 8, Connecticut.
SECOND QUARTERLY REPORT ON RESEARCH AND DEVELOPMENT OF TITANIUM ROCKET MOTOR CASES, by R. P. Brody and F. A. Crosby, January 31, 1961. 101 p. incl. illus. (Project No. TB4-004) Contract No. DA-19-020-ORD-5230

Unclassified Report

The results of work performed during the quarter from October 1 through December 31, 1960 on the development of a high strength, lightweight, titanium alloy rocket case, are reported. These results include 1) tensile tests, chemical analysis, and microexamination of a press-forged pancake forging, 2) tech-
(over)

UNCLASSIFIED

1. Rockets, Motor Cases
2. Titanium Fabrication
3. Titanium Alloys

I. Brody, R. P. and Crosby, F. A.
II. U. S. Army Ordnance Corps, Watertown Arsenal
III. Contract DA-19-020-ORD-5230

Pratt & Whitney Aircraft Division of United Aircraft Corporation, East Hartford 8, Connecticut.
SECOND QUARTERLY REPORT ON RESEARCH AND DEVELOPMENT OF TITANIUM ROCKET MOTOR CASES, by R. P. Brody and F. A. Crosby, January 31, 1961. 101 p. incl. illus. (Project No. TB4-004) Contract No. DA-19-020-ORD-5230

Unclassified Report

The results of work performed during the quarter from October 1 through December 31, 1960 on the development of a high strength, lightweight, titanium alloy rocket case, are reported. These results include 1) tensile tests, chemical analysis, and microexamination of a press-forged pancake forging, 2) tech-
(over)

UNCLASSIFIED

1. Rockets, Motor Cases
2. Titanium Fabrication
3. Titanium Alloys

I. Brody, R. P. and Crosby, F. A.
II. U. S. Army Ordnance Corps, Watertown Arsenal
III. Contract DA-19-020-ORD-5230

Pratt & Whitney Aircraft Division of United Aircraft Corporation, East Hartford 8, Connecticut.
SECOND QUARTERLY REPORT ON RESEARCH AND DEVELOPMENT OF TITANIUM ROCKET MOTOR CASES, by R. P. Brody and F. A. Crosby, January 31, 1961. 101 p. incl. illus. (Project No. TB4-004) Contract No. DA-19-020-ORD-5230

Unclassified Report

The results of work performed during the quarter from October 1 through December 31, 1960 on the development of a high strength, lightweight, titanium alloy rocket case, are reported. These results include 1) tensile tests, chemical analysis, and microexamination of a press-forged pancake forging, 2) tech-
(over)

UNCLASSIFIED

1. Rockets, Motor Cases
2. Titanium Fabrication
3. Titanium Alloys

I. Brody, R. P. and Crosby, F. A.
II. U. S. Army Ordnance Corps, Watertown Arsenal
III. Contract DA-19-020-ORD-5230

niques for hydrogenation of B-120VCA sheet stock, 3) fracture toughness and modified Charpy impact tests on flow-turned material, 4) x-ray diffraction studies of cold-rolled and flow-turned material, 5) tensile, bend, and fracture toughness tests of TIG and electron-beam welds, and 6) tensile tests of pancakes forged at high and low strain rates.

niques for hydrogenation of B-120VCA sheet stock, 3) fracture toughness and modified Charpy impact tests on flow-turned material, 4) x-ray diffraction studies of cold-rolled and flow-turned material, 5) tensile, bend, and fracture toughness tests of TIG and electron-beam welds, and 6) tensile tests of pancakes forged at high and low strain rates.

niques for hydrogenation of B-120VCA sheet stock, 3) fracture toughness and modified Charpy impact tests on flow-turned material, 4) x-ray diffraction studies of cold-rolled and flow-turned material, 5) tensile, bend, and fracture toughness tests of TIG and electron-beam welds, and 6) tensile tests of pancakes forged at high and low strain rates.

niques for hydrogenation of B-120VCA sheet stock, 3) fracture toughness and modified Charpy impact tests on flow-turned material, 4) x-ray diffraction studies of cold-rolled and flow-turned material, 5) tensile, bend, and fracture toughness tests of TIG and electron-beam welds, and 6) tensile tests of pancakes forged at high and low strain rates.

DISTRIBUTION LIST

To:	No. of Copies
Commander Armed Services Technical Information Agency Arlington Hall Station Arlington 12, Virginia Attn: TIPDR	10
Solid Propellant Information Agency Applied Physics Laboratory The Johns Hopkins University Silver Spring, Maryland	3
Defense Metals Information Center Battelle Memorial Institute Columbus, Ohio	1
Office Chief of Ordnance Department of the Army Washington 25, D. C. Attn: ORDTB - Materials	1
Advanced Research Projects Agency The Pentagon Washington 25, D. C. Attn: Dr. M. C. Kay	1
Commanding General Frankford Arsenal Philadelphia 37, Pa. Attn: ORDBA, N. H. Markus Attn: ORDBA, Dr. H. Gisser	1 1
Commanding General Watertown Arsenal Watertown 72, Mass. Attn: ORDBE-LX	5
Commanding Officer Ordnance Materials Research Office Watertown Arsenal Watertown 72, Mass. Attn: [illegible]	1
Commanding General U. S. Army Rocket and Guided Missile Agency Redstone Arsenal, Alabama Attn: ORDXR-OCP, Mr. R. L. Wetherington	1
Commanding General Army Ballistic Missile Agency Redstone Arsenal, Alabama Attn: Dr. G. H. Reisig	1
Commanding General Aberdeen Proving Ground Aberdeen Proving Ground, Maryland Attn: Dr. C. Pickett, [illegible]	1
Commanding Officer Picatinny Arsenal Dover, N.J. Attn: Plastics & Packaging Laboratory	1
Commanding Officer Rock Island Arsenal Rock Island, Illinois Attn: Materials Section Laboratory	1
Alloyd Research Corporation 35 Cambridge Parkway Cambridge, Mass. Attn: Dr. S. S. White	1
Battelle Memorial Institute 505 King Avenue Columbus 1, Ohio Attn: Mr. R. Monroe Mr. O. Faulkner	1 1
Lyon, Inc. Detroit, Michigan Attn: W. Marlin	1
Commanding Officer Boston Ordnance District Army Base Boston 10, Massachusetts Attn: Research & Development Branch ORDSB-[illegible]	1
George C. Marshall Space Flight Center National Aeronautics and Space Administration Redstone Arsenal, Alabama Attn: Dr. W. Lucas	1

To:	No. of Copies
Commanding General U. S. Army Ballistic Missile Agency Huntsville, Alabama Attn: Mr. H. Hinrichs Propulsion Laboratory	1
Superintendent U. S. Naval Weapons Plant Washington 25, D. C. Attn: Code 722	1
General Electric Company Rocket Engine Section Flight Propulsion Laboratory Department Cincinnati 15, Ohio	1
Office of the Director of Defense Research & Engineering Room 3E-1065, The Pentagon Washington 25, D. C. Attn: Mr. J. C. Barrett	1
Department of the Navy Bureau of Ordnance Room [illegible], Main Navy Bldg. Washington 25, D. C. Attn: Commander H. O. Salter, ReS6	1
U. S. Air Force Directorate of Research & Development Room 4D-313, The Pentagon Washington 25, D. C. Attn: Lt. Col. J. P. Shipp, Jr.	1
Commander Army Research Office Arlington Hall Station Arlington 12, Virginia	1
National Aeronautics and Space Administration Washington, D. C. Attn: Mr. R. V. Rhode	1
Wright Air Development Center Wright-Patterson Air Force Base, Ohio Attn: Materials Central ([illegible])	5

To:	No. of Copies
AFFTC Flight Test Center Edwards Air Force Base, California Attn: Solid Rocket Branch (FTRS)	5
ASC Aeronautical Systems Center Wright-Patterson Air Force Base, Ohio Attn: Mfg. & Material Technology Division [illegible]	10
Commander U. S. Naval Ordnance Laboratory White Oak, Silver Spring, Maryland Attn: Code WM	1
Commander U. S. Naval Ordnance Test Station China Lake, California Attn: Technical Library Branch	1
Department of the Navy Office of Naval Research Washington 25, D. C. Attn: Code 423	1
Department of the Navy Special Projects Office Washington 25, D. C. Attn: SP 271	1
Atlantic Research Corporation Shirley Highway and Edsall Road Alexandria, Virginia Attn: Mr. E. A. Olcott	1
Aerojet-General Corporation Post Office Box 1168 Sacramento, California Attn: Librarian	1
Aerojet-General Corporation Post Office Box 296 Azusa, California Attn: Librarian	1
Mr. C. A. Fournier	1

To:	No. of Copies
Hercules Powder Company Allegany Ballistics Laboratory Post Office Box 210 Cumberland, Maryland Attn: Dr. R. Steinberger	1
Arthur D. Little, Inc. Acorn Park Cambridge 40, Mass. Attn: Dr. Bindari	1
[illegible]-Portland, Inc. 71 [illegible] Street Newark 2, N.J. Attn: E. Bressel	1
The Budd Company Defense Division Philadelphia 32, Pa. Attn: R. C. Dethlorg	1
Curtiss-Wright Corporation Wright Aeronautical Division Wood-Ridge, N. J. Attn: Mr. H. Hahn Mr. A. M. Nettle	1 1
Borg-Warner Ingersoll Kalamazoo Division 1810 N. Pitcher Street Kalamazoo, Michigan Attn: Mr. L. E. Hershey Mr. R. E. Anperman	1 1
Massachusetts Institute of Technology Cambridge, Massachusetts Attn: Prof. Backofen	1
Mellon Institute 4400 Fifth Avenue Pittsburgh 13, Pa. Attn: C. J. Owen Dr. H. L. Anthony	1 1
Titanium Metal Corporation of America 233 Broadway New York 7, New York Attn: Mr. Ward W. Minkler	1
Republic Steel Company Farmingdale, Long Island, N.Y. Attn: Mr. Thomas Perry	1

To:	No. of Copies
Manufacturing Laboratories 249 Fifth Street Cambridge 42, Mass. Attn: Dr. P. Fopiano Dr. V. Radcliffe	1 1
Ohio State University Research Foundation Columbus, Ohio Attn: Dr. McMaster	1
Advanced Metals Research Corp. 625 McGrath Highway Somerville, Mass. Attn: Mr. Lewis	1
Perkin-Elmer Corp. Main Avenue Norwalk, Connecticut Attn: Mr. J. Beardsley	1
Jet Propulsion Laboratory California Institute of Technology 4800 Oak Grove Drive Pasadena, California Attn: Dr. L. Jaffee	1
Ladish Company Cudahy, Wisconsin Attn: Robert P. Daykin Research Metallurgist	1
Wyman-Gordon Company Grafton, Massachusetts Attn: Arnold Rustay Director of Research	1
George C. Marshall Space Flight Center Huntsville, Alabama Attn: William A. Wilson M-F&AE-[illegible]	1
Crucible Steel Company Midland, Pennsylvania Attn: Dr. Walter Finlay	
Reactive Metals, Inc. Niles, Ohio Attn: Mr. E. N. Lundstrom	1